AIRCRAFT SURVIVABILITY

Fall 2003

Reclaiming the Low Altitude Battlespace

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JOINT AIRCRAFT SURVIVABILITY
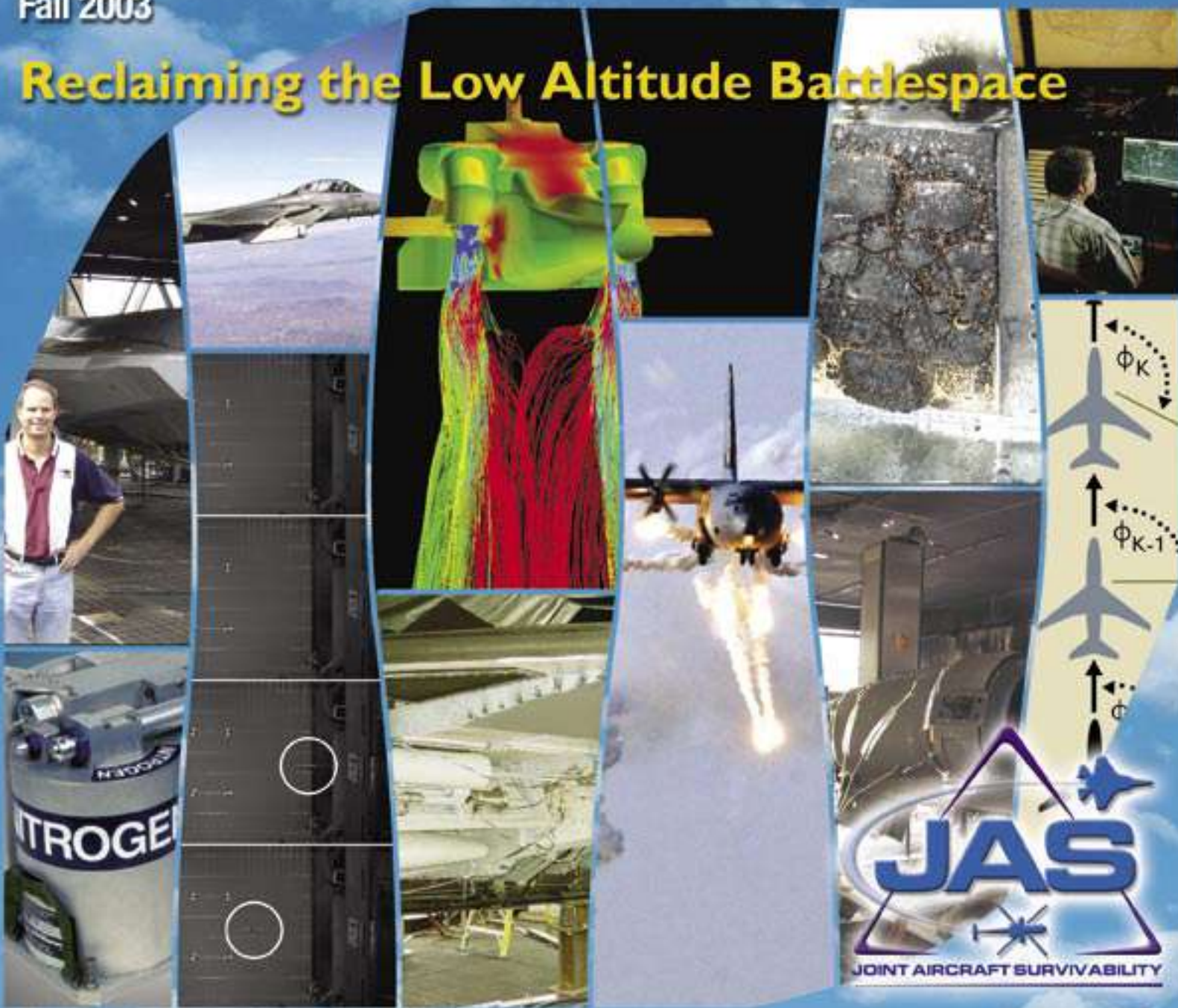
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Photo by SSgt. David Nolan

JASPO PM's Notes

CDR Andrew (Andy) Cibula

This edition of the *Aircraft Survivability* Journal focuses on reclaiming the low-altitude battlespace. By saying that we need to reclaim the low-altitude battlespace, I imply that we have already lost that area of combat operations. I think many will argue that point, but I also think that we can safely say that if we have not given it up entirely, we have definitely retreated from using it as we would like. In general, helicopter operations will always need to take place under 15,000 feet. Fighter aircraft can mostly avoid low altitudes if necessary, but will often perform missions at lower altitudes. And transport and reconnaissance aircraft may operate in these altitudes, but they most certainly spend quite a bit of time transitioning through. So if all our aircraft use this airspace, why did we ever give it up at all?

In the last 40 or so years, aircraft survivability has shifted away from damage tolerance to hit avoidance. As technology advanced and threats became more lethal, it made a lot of sense to keep the aircraft from being hit in the first place. With advanced countermeasures and low observable technology, this was possible. But there was also another factor that shifted our focus away from protecting our aircraft down low. As our technology increased and we were able to outfit our aircraft with a lot of high-tech gizmos, the focus shifted from developing vulnerability reduction features to developing advanced sensors for threat detection, engagement, and target destruction at greater distances. You see, if you can detect and identify a threat at 500 miles, engage it at 450 and destroy it at 400, there really isn't a need to worry about getting hit. The only problem with that is—we aren't there yet. We are still developing requirements documents that define missions in the lower altitudes, and we still need to transition through the lower altitudes for takeoff and landing while sometimes using forward bases that are not that secure. And someone forgot to ask the helo guys what they thought of this strategy.

If you took a poll of operators in the fleet and asked them what they wanted most on their aircraft, they would say—

1) advanced sensors,

2) range and speed,

3) long range and very accurate weapons,

4) low observable technology, and

50) vulnerability reduction.

Yes that was number 50, not number 5. There are two reasons for this. First, vulnerability reduction technology is not very sexy. A cool new radar that can identify a target at 500 miles is always preferable to a fuel tank liner. And second, most operators just assume that basic vulnerability reduction features such as fire protection and redundancy are a given in aircraft design. If you asked an operator if he would prefer target ID at only 400 miles while guaranteeing he would not burn up in flight because of a fuel leak, you might get a different answer.
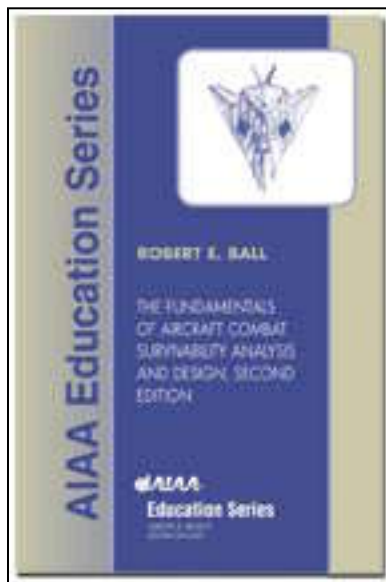
As you go through this issue, keep in mind that vulnerability reduction and defeating the IR threat are still a very important part of the overall survivability equation. Until we can truly develop technologies that can keep our aircraft from being hit in combat, this will be the case.

CDR Andrew (Andy) Cibula

News Notes

■ by Mr. Joseph Jolley

Aircraft Survivability Short Course

The Joint Aircraft Survivability Program Office (JASPO) is sponsoring a three-day Aircraft Survivability Short Course to be held November 18-20, 2003. This orientation course will be taught at a location in Williamsburg, Virginia. The course is already full, with the majority of attendees coming from the Army Aviation Applied Technology Directorate at Ft. Eustis. NASA Langley will also have a small number attending. The course will cover a broad spectrum of topics relating to aircraft combat survivability. Although this course is full, there will be other opportunities to attend future offerings.

SURVIAC Offers New Customer Service

The Survivability/Vulnerability Information Analysis Center (SURVIAC) is now offering a new service to its customers called SURVIAC E–News. The first edition has been emailed to those who are currently receiving other SURVIAC publications, products or services. SURVIAC E–News provides a quick reference resource of current survivability information catalogued by subject and date. If you wish to subscribe or find out more

about E–News, contact SURVIAC at 937/255.4840 or visit their Web site at http://www.bahdayton.com/surviac.

NDIA Recognizes Outstanding Accomplishment

The National Defense Industrial Association's (NDIA) Aircraft Survivability Symposium 2003 was held again this year in Monterey, California at the Naval Post Graduate School, November 3-6, 2003. This year's theme was "Reclaiming The Low Altitude Battlespace." Each year during the symposium, the NDIA presents two awards—the Combat Survivability Award for Technical Achievement and the Combat Survivability Award for Leadership. This year's Technical Achievement award was presented to Dr. Lewis Thurman, Principal, at MIT Lincoln Lab. This year's Leadership award was presented to Mr. James Foulk, President, SURVICE Engineering Company, and a founding member of the Combat Survivability Division. Our next issue of Aircraft Survivability will have an article that includes highlights of the symposium.

Key Personnel Changes

JASPO is experiencing changes in key management positions. Recently, Mr. John Kamadulski replaced Dr. Steven Messervy as the Army Principal Member. Mr. Kamadulski comes from the Aviation Electronic System Project Office at Redstone Arsenal, Alabama. Dr. Messervy has

accepted a new position as Deputy Program Manager of the Joint Simulations System program office at the Research Park in Orlando, Florida. Also, Mr. Hugh Griffis has replaced Mr. Dick Colclough as the Air Force Principal Member. Mr. Colclough has retired. Mr. Griffis comes from the Aeronautical Systems Center Engineering Directorate, Air Force Materiel Command at Wright-Patterson AFB, Ohio. Mr. Tim Horton from the Naval Air Warfare Center, Weapons Division, China Lake, California, continues as the Navy's Principal Member. Finally, CDR Andy Cibula, JASPO Program Manager, will be rotating back to the NRO in January 04. His replacement will be LCDR Dan Chisholm, also from the NRO.

AFMC Announces New DT&E Structure

The Air Force Materiel Command (AFMC) announced on August 20th that a new Developmental Test and Evaluation (DT&E) enterprise would stand up October 1st. This new enterprise would bring under one organization the Arnold Engineering Development Center, Tennessee; the Air Force Test Pilot School at Edwards AFB, California; and the service's Landing Gear and Live Fire Test Facilities, which includes the Aerospace Survivability and Safety Flight of the 46th Test Wing. The first phase is scheduled to last one year, and is considered a trial run in creating the DT&E enterprise. The reorganization stems from the Air Force's announcement to restructure the program executive officers, the decrease in military resources, and new information-related technologies that allow for increased efficiencies in information flow. Goals of the new organization include the ability to offer total cost visibility and to improve the business of test and evaluation. ■

Next Generation IR Engine Suppression

■ by Ms. Kellie B. Unsworth, and Mr. Revis T. Napier

Recent events have focused an increased interest within the aircraft survivability community on a multitude of weapon systems. Some of these weapons are relatively new, but many are threats or upgrades to threats encountered in the past. The proliferation, both in number and geographical extent of these threat systems has increased the likelihood of an encounter with one of our aircraft systems. The survivability community has been hard at work, addressing many of these threats through system improvement to existing survivability equipment, and signature control features of the current fleet. Particularly challenging for helicopter systems survivability is the environment in which they operate. Typically, helicopters operate in physically rugged environments. Survivability solutions that vie for a place on today's fleet helicopter must not only be effective in allowing the helicopter to avoid or defeat the threat, but also must address the "ilities"—reliability, maintainability, durability, vulnerability, etcetera, while balancing air-vehicle weight and mission performance issues. Technology evolution has facilitated expanded performance capabilities of these platforms, but typically at the price of added weight to the airframe. Current fielded Army helicopter platforms were developed back in the 70s and 80s. Suppressor technology developed during that era—like the Hover Infrared Suppressor System (HIRSS) deployed on the UH–60/CH–60 helicopters and the Black Hole suppressor on the AH–64 helicopter—was designed to defeat Band I threats, such as the SA–7 (Figures 1 and 2). Twenty years later, upgraded engines, which produce hotter exhaust tempera-

tures, along with improved, Band IV detector technology, have resulted in a three to five times increase in the in-band infrared (IR) signature of typical helicopter targets, with a corresponding 170–230 percent increase in lock-on range. Additionally, these Band IV seekers often employ jam resistant signal processing and decoy discrimination logic, decreasing the effectiveness of active countermeasures and increasing the burden on passive signature reduction to prevent the initial engagement. Much effort has been spent attempting to develop advanced engine IR suppressor systems for helicopter platforms that meet the increasingly lethal and proliferated threat we are seeing today, as well as looking ahead to the threats we anticipate in the near future. Technologies have been demonstrated that provide a significant boost in signature reduction. Unfortunately, the penalty to the aircraft for these improvements has often been unacceptable in terms of engine horsepower loss, fuel burn, and system weight. Oftentimes, a less than ideal survivability protection system is accepted for helicopters as a result of the effort to balance improved survivability with performance degradation and resulting in reduced payload/range. As a result, one of the primary focuses of the survivability community is developing technologies that provide the right levels of survivability for the right period of time during threat encounters, while minimizing the performance impact to the helicopter during non-threat encounters.

Reactive IR Suppressor Program

The Army's Aviation Applied Technology Directorate (AATD), at Fort Eustis, Virginia, initiated a

research and development program, jointly funded by JASPO in the fall of 2002 to design, fabricate, and test a reactive engine exhaust IR signature control system for rotary-wing application. The uniqueness of this IR suppressor system lies in its capability of providing both significantly greater signature reduction than current fixed nozzle/ejector systems, while minimizing, or eliminating engine performance penalties when operating unsuppressed in low threat environments.

The goal of this program is to develop and test a Reactive IR Engine suppressor system that provides in the suppressed or threat mode, up to a 75 percent reduction in IR signature on demand while maintain-

Figure 1. Apache — Black Hole

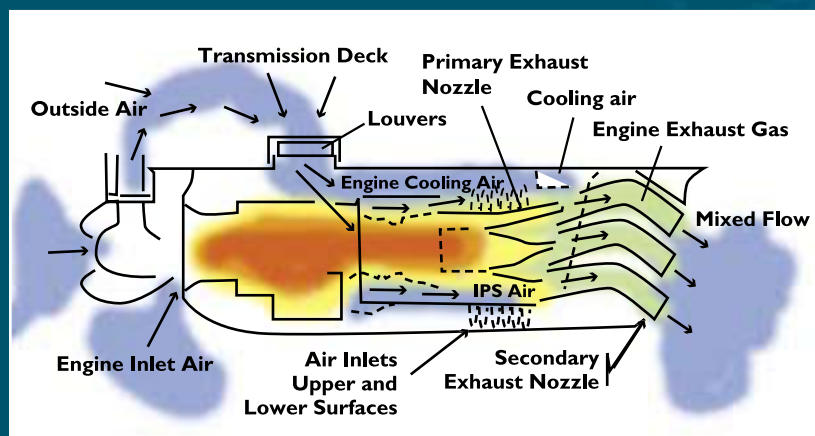Figure 2. Blackhawk—HIRSS Reactive IR Suppressor Program

Figure 3. Engine airflow management system (Courtesy of Boeing Mesa)

ing an engine performance penalty no worse than the baseline Apache with the Black Hole suppressor. Additionally, a 75 percent reduction in engine performance penalties during unsuppressed or non-threat operations is also a goal. The Reactive IR system design is similar to the Rolls Royce/Lockheed Martin JSF 3 bearing swivel duct in its ability to efficiently change the direction of the exhaust. The Reactive IR suppressor uses this technique, with only two swivel ducts, to eliminate the line-of-sight to hot metal in the engine. A graphite epoxy aerogel-impregnated honeycomb ejector shroud will surround the primary nozzle and provide the air gap for the secondary pumped airflow. The aerogel-filled composite shroud technology was developed under the Lightweight Thermal Insulation program, another joint AATD and JASPO program, and has been demonstrated to provide a very efficient thermal barrier to moderate temperature environments, such as this application. The combination of exhaust duct turning and insulated, near-ambient exhaust structure temps effectively "winks out" the exhaust IR signature within one to two seconds.

AATD as the lead design agent, assembled a support team for the concept formulation and screening phase. This team is comprised of Allied Aerospace Inc, General Electric Aircraft Engines, Sikorsky Aircraft, Dynetics, and CAS, Inc. During the first phase of the program, the baseline Apache Black Hole suppressor and a modular proof-of-concept

Reactive IR Suppressor system were tested at AATD's Countermeasures Test Facility (CTF). In addition to collecting baseline Apache data for test reference, the initial test phase was geared to screen Reactive IR suppressor design features and optimize parameters such as suppressor size, pumping efficiency, engine performance, and engine bay cooling as well as to characterize the IR signature of the system. Data was collected and assessed in these areas with the modular hardware in both the "unsuppressed" and the "fully suppressed" modes.

Baseline Testing—AH–64 Apache

Aircraft integration is a crucial element in the design of any new IR suppressor system. Of particular importance for the Reactive IR Suppressor are weight/balance, aerodynamic drag, structural analysis and mounting, integration of the actuation system, and handling qualities issues. While the Reactive IR suppressor concept lends itself well to several current fleet helicopters, the AH–64 Apache was selected as the surrogate aircraft for this development program. AATD's CTF consists of an engine test cell equipped with a GE T70–GE–701C engine and controlled by a waterbrake system, an engine control room and data collection system, and a fabrication/mockup facility. The current Apache Black Hole suppressor system, including the engine nacelle and oil cooler was integrated into the CTF setup to provide accurate baseline data on both the Apache air management

system and the IR signature. The current Apache Black Hole system is comprised of a three high aspect ratio primary nozzle assembly that exhausts into three separate ejector/baffles, canted 45 degrees to break line-of-sight to engine hot parts. The suppressor cools the flow in two stages—first, the ejector system pulls cool ambient air across the oil cooler and through the engine bay, providing critical engine cooling before it reaches the ejector baffles. Upper and lower vents in the engine cowling draw in additional cooling air to mix with the hot primary flow and dilute the exhaust temps. Cooling air is pulled across the oil cooler by means of pumping, caused by the three-nozzle set-up. Additionally, multiple rows of cooling fins attached to each ejector baffle aid in the dissipation of the heat (Figure 3). The Apache engine cowling and suppressor were coupled to a T700–701C engine as a baseline configuration and was tested at CTF in early June 2003. Engine performance data, pumping and engine bay flows, as well as IR signature data were collected for this baseline. This data was used for comparison purposes with the Reactive IR suppressor design to assess the goals of maintaining existing Apache engine bay flows while reducing the engine performance penalty and IR signatures by 75 percent each.

Modular Proof-of-Concept Hardware

Modular proof-of-concept hardware for the Reactive IR suppressor system was integrated with the Apache engine nacelle on the CTF test stand in late June 2003. The primary goal of the modular hardware was to allow efficient parametric testing of key suppressor design features. Various inner/outer duct diameter combinations, as well as numerous extensions to the outer duct length, were evaluated to provide data to guide in designing the prototype Reactive IR suppressor. Matching the pumping characteristics of the AH–64 Black Hole suppressor was of paramount importance as well as the desire to keep the Reactive IR suppressor profile within the footprint of the existing Apache suppressor on the aircraft. Initial ground test hardware was fabricated using inconel inner
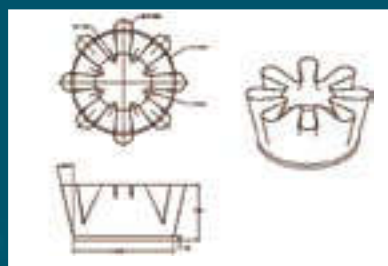
Figure 4. Proof of concept Reactive IR Suppressor

Figure 6. Reactive Suppressor lobed nozzle

Figure 5. Apache Computational Fluid Dynamics Models

duct/nozzles and a stainless steel outer duct wrapped in a surrogate insulation system of the same thermal conductivity as the aerogel-filled honeycomb. Swivel duct flanges and Voss V-band clamps on the inner and outer ducts allow the system to be manually rotated through the full range of 0 – 90 degrees for this testing. The prototype design, scheduled to begin fabrication in late 2003, will demonstrate the capability of a two second response time from unsuppressed to fully suppressed with either a hydraulic or electric motor. Figure 4 depicts the proof-of-concept Reactive IR Suppressor design that was tested at CTF.

Analytic Modeling

Computational Fluid Dynamics (CFD) analysis was conducted in support of the suppressor design development. A key aspect of the design was the need to keep the engine plume from impinging on the airframe and contributing to the skin thermal emissions of the aircraft, as these emission sources would persist after the reactive suppressor system is activated. A high fidelity (>15 million grid point) CFD model of the AH–64 with the Reactive IR suppressor was developed by Dynetics, under contract to the Army, to assess

plume impingement of the AH–64 in various operational modes. Flow results indicate that the reactive suppressor exhaust canted 15 degrees off axis is sufficient to preclude impingement under normal flight conditions, while also minimizing additional aero drag and engine performance loss. Assessment of the rotor downwash was included in the analysis—an important benefit of the analysis since accurate rotor downwash effects cannot be replicated at CTF. In addition to the typical rotor downwash velocity distribution as a function of distance from the rotor, a swirl component representing 10 percent of the downward velocity magnitude was imposed in the plane of the rotor. The CFD analysis of the unsuppressed flow indicates little plume impingement of the airframe in all operating modes with the suppressor canted 15 degrees off axis. Very limited signature impact was noted in the suppressed configuration. The signature impact of minor convective thermal transfer between the plume and airframe, typical of both the existing Apache suppressor and the Reactive system, can easily be minimized through the use of existing low-emissivity coatings.

Dynetics also conducted a threat analysis, utilizing the high fidelity DISAMS code, to assess the ability of the Reactive suppressor system, with and without active countermeasures, to defeat advanced MANPADS threats. A notional aircraft target was used and two typical MANPADS threat systems selected for this study. The aircraft target was equipped with both the Reactive IR

suppressor and a currently-fielded jammer system. A parametric study to assess miss distance versus aircraft signature was accomplished as well as analysis of aircraft survivability as a function of countermeasures and latency times. Vignettes, including both low altitude hover and forward flight scenarios were provided by the Army Battle Labs (AMBL) and were used for this analysis. The basic results from the parametric study indicate signature reduction alone is not sufficient to protect the aircraft. Moreover, significant aircraft signature suppression is required to provide sufficient Jam to Signal (J/S) for current jammer systems to successfully defeat MANPADS threats. Suppressor study results support the need for a reactive suppressor system that responds quickly (< two seconds) or stays on during a high threat mission against short-range threats. During the longer range engagement scenarios, extended reaction times, up to six seconds were found to beeffective with the reactive suppressor system.

Proof-of-Concept Data Results

Data obtained from the ground test set-up has strongly supported the reactive suppressor concept. The engine bay pumping has been demonstrated at 95 percent in the unsuppressed mode and 86 percent in the suppressed mode of the AH–64 baseline system. Discussions with Boeing personnel have confirmed that the baseline Apache system produces high engine cooling margins and that these bay flows achieved in the proof-of-concept hardware are

more than adequate to maintain oil temperatures within specification in all flight regimes.

Engine performance data for the proof-of-concept hardware exceeds expectations. A 79 percent decrease in engine performance penalty in the unsuppressed mode and a 34 percent reduction in performance penalty in the suppressed mode was achieved relative to the AH–64 Apache baseline. Referencing the Reactive IR suppressor proof-of-concept hardware coupled to the T700-GE-701C engine with the referee nozzle, ground test results measured approximately 0.6 percent shaft horsepower loss in the unsuppressed configuration and 1.9 percent shaft horsepower loss in the fully suppressed configuration. Comparatively, baseline AH–64 Black Hole suppressor shaft horsepower loss was 2.9 percent. Initial program goals identified a 75 percent reduction in engine performance penalty in for the Reactive Suppressor in the unsuppressed configuration. In the suppressed configuration, the assumption was that the engine could tolerate a horsepower loss somewhat greater than what is currently flown on the AH–64 with the Black Hole suppressor for limited duration timelines when the aircraft was in an engagement avoidance mode or identified high threat area. It was a pleasant revelation during the ground test phase that in fact, the Reactive IR suppressor could buy back significant engine performance in both the unsuppressed and the suppressed modes when compared to the baseline AH–64. This translates into substantial payload/range increases on the order of 4-14 nm additional range and 80-225 lbs. additional payload for an AH–64 Apache, when equipped with an upgraded drive system to include a 3400 HP main transmission and engine nose gearbox. Even without the payload/range benefits available in conjunction with the upgraded transmission system, substantial fuel savings would be realized by the 1–2.3 percent engine performance improvement.

IR signature data was collected in the 3 to 5 micron band on the proof-of-concept hardware as well as on the Apache Black Hole baseline on the test stand at CTF. Insulation representative of the thermal conductivity achieved in aerogel-filled honeycomb structures was used as a surrogate on the Reactive Suppressor proof-of-concept hardware. This was done primarily to save the expense of fabricating aerogel-filled structural components during this proof-of-concept phase, when the secondary shroud tested was still significantly longer and not the desired final design for the reactive IR Suppressor system. AATD's IR data collection system was calibrated and set-up in order to maximize the signature of both the new suppressor concept and the baseline Black hole suppressor. The resulting data, which was averaged over three power settings (IRP, max continuous, and max) demonstrated a 67 percent reduction in IR signature of the Reactive Suppressor concept over the baseline Black hole system. Additional IR testing to achieve the full 75 percent desired signature reduction stated in the program goals will be accomplished during the next phase with a Reactive Suppressor prototype.

The last phase of the proof-of-concept hardware testing is underway. A lobed primary nozzle is being fabricated that will improve primary/secondary air mixing and allow substantial shortening of the secondary shroud length. This lobed primary nozzle, which will maintain the same exit plane area as the surrogate tested primary nozzle, will result in similar low turbine backpressure. It is expected that the lobed nozzle will allow the mixing duct (or secondary shroud) length to be reduced by at least half, permitting the prototype design to fit in the same profile on the aircraft as the current Black Hole suppressor, while weighing very close to the same per shipset as the Black Hole. Temperature measurements in the secondary shroud flanges indicate that the use of lightweight Titanium should be achievable in the final design. Weight estimates for the production design are 160-200 lbs per shipset with the low-end weight based on using the lightweight Titanium. Minimizing impact to total aircraft system weight and any shift in aircraft center of gravity was a primary program goal. A lobed nozzle as shown in Figure 6 is being fabricated.

Path Forward

The Army fleet needs an improved IR suppressor. Threat systems continue to evolve, yet the 20-year-old suppression technology continues to be in operation in the fleet. Evolution of Band IV seekers calls for a new approach to defeat them. The proof-of-concept Reactive IR Suppressor hardware ground tested at AATD's CTF demonstrates significant promise, both in terms of aircraft survivability as well as in terms of payload/range and fleet fuel saving. With the Reactive IR Suppressor's demonstrated engine performance enhancement, the aircraft will have increased loiter time and a broader mission capability. The combination of engine performance improvement and encouraging IR signatures measured together make the concept of the Reactive IR Suppressor very attractive for rotorcraft vehicles. During the next phase of the program, the test data and information collected in the proof-of-concept stage will be complied and a detailed design developed, and an actuated Reactive Suppressor prototype produced. Ground testing of the prototype to aid in the airworthiness evaluation will culminate in FY04. Flight hardware fabrication and test aircraft integration are planned for FY05 with flight-testing scheduled for late FY05.

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F/A–22 IR Signature Flight Test Model Validation

■ by Mr. Jim Cline, Dr. Denny Behm, Ms. Karen Kidd, and Mr. Kevin Young

During the last 40 years infrared (IR) guided missiles have been the leading killer of combat aircraft. The enemy may use radar to acquire and track their targets, but historically kills from IR missiles have predominated. Although improvements in IR seeker lock-on ranges, infrared counter countermeasures (IRCCM), and high off–bore site launching and tracking continue to make them the short-to-mid range weapon of choice, it is the recent emergence of long-range IR Search and Track (IRST) Systems as the Air Interceptor's primary acquisition sensor that represents a significant counter-stealth challenge to U.S. high-performance fighters. The significant U.S. strides to mitigate the threat's use of the radio frequency spectrum have forced foreign countries to develop these "IR radars" in an attempt to regain previous radar acquisition ranges. Understanding and controlling aircraft IR signature will be an essential element in addressing the mission effectiveness of future conflicts.

Introduction and Requirements

This article describes the successful validation of the F/A–22 IR signature prediction model using in-flight IR radiometric measurements as contractually required to demonstrate compliance with the F/A–22 Program's IR Signature Specification. The F/A–22 IR signature specification consists of four tables (2 Flight Conditions: M1.5/40kft and M0.9/30kft for 2 Wavebands: 3.5–5 and 8–12 microns) with 26 Az/El view angles that specify the maximum
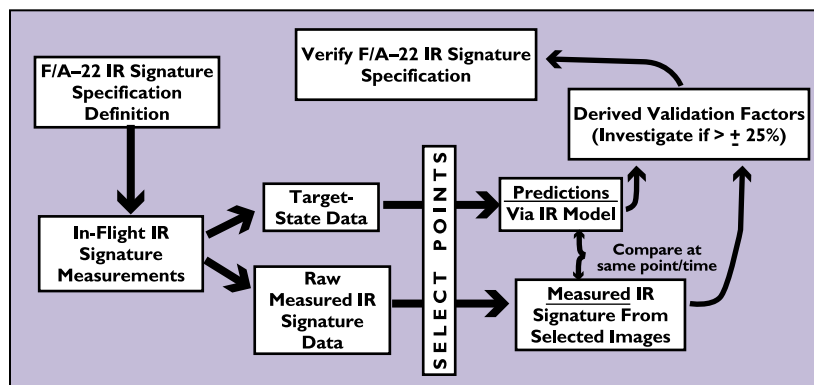

Figure 1. F/A–22 IR Signature Model Validation Process

Figure 2. F/A–22 In-flight Infared Signature Measurements (left to right: F–15B with NAWC's Tiger IR Measurement Pod, and F/A–22 Test Aircraft)

allowable IR signature (source non-contrast Watts/sr). The wording of the IR spec necessitates validating an IR signature prediction model using flight test measurements and then running the model at exact specification conditions to demonstrate IR spec compliance (after flight-test-derived "validation factors" have been applied; Figure 1).

During IR model validation, if the predicted signature was within +/- 25 percent of the measured signature, then a validation factor was established, and validation of the test point was considered complete. If the predicted signature was not within +/-25 percent of the measured signature then the test point was diagnosed to determine the cause of the discrepancy. If the cause could be easily "fixed," or alternately modeled, then it was. However, if the cause could not easily be fixed

Figure 3. NAWC Pt. Mugu Tiger IR Signature Measurement Pod

Figure 4. Tiger Pod Operator Video

then the SPO was notified, and a decision was made to either fix the discrepancy or not. In either case a validation factor was established for this test point. Separate requirements from AFOTEC added additional flight conditions, plume-model validation, and transient response. Characterization to flight testing and IR model validation activities (will not be discussed here).

IR Signature Model
The Lockheed Martin developed Spectral Imaging (SIMIR) IR signature code was approved by the F/A–22 SPO for flight test validation usage and subsequent IR spec verification predictions. SIMIR predicts the IR signature of aircraft from 0.4 to 25 µm and outputs IR images, spectral and in-band IR radiant intensity (Watts/sr), signature source contribution, and calculates sensor detection/lock-on range. To create the high fidelity F/A–22 IR model, SIMIR utilizes inputs (geometry, temperatures, material placement/performance, etc.) obtained from lab coupon testing, F119 engine runs, and measurements/predictions from F/A–22 Teammates.

Flight Testing
IR testing was performed at Edwards AFB (EAFB) during the Fall of 2000 on F/A–22 instrumented test aircraft 4002 with production configuration engines and IR topcoats (Figure 2). Thirteen sorties were flown mostly over water at the Naval Air Warfare Center's (NAWC) Weapons Division Sea Test Range and resulted in obtaining approximately 17 hours of in-flight IR signature data. IR signature measurements were taken using an EAFB–based F–15B equipped with the NAWC ATIMS IV (a.k.a. Tiger) IR pod. The Tiger pod's ability to simultaneously acquire four wavebands of high-dynamic-range IR-calibrated digital movies over wide Az/El viewing angles at sustained supersonic speeds (Figure 3) was critical to obtaining needed IR model validation data. The back-seat operator joy-stick-slews the Tiger Pod's turret towards the target using a bore-sighted video camera that displays turret Az/El pointing angle and range (Figure 4). High-resolution radiometrically calibrated IR "mov-

ies" are digitally recorded at a 24 Hz frame rate (6 Hz for four gain states) for the mid waveband (MWIR) cameras and at 1 Hz for the long waveband (LWIR) imager. IR imager drift was checked in-flight about every 15 minutes by viewing a large, very black-felt appliqué applied to the outboard of the right vertical tail (seen in Figure 2) that served as a near-blackbody reference (all actual target measurements were performed on 4002's left hemisphere only).

Quick-look data review was performed after each test sortie to ensure data integrity for later reduction/analysis. If for any reason critically-defined IR or target-state data were not properly recorded, those flight test points were repeated (this was less than 5 percent). Over 45 temperature sensors were applied to ship 4002's exterior airframe surface (and aft-only portions of the exhaust system's sidewall), which was already instrumented heavily for propulsion testing. From an IR perspective, ship 4002 as tested was as close to a production F/A–22 configuration as possible (F119 production representative engines and airframe geometry and exterior coating placement/performance).

Data Reduction
At the completion of all flight testing specific time intervals were defined for needed IR and target-state data to cover the required validation points described previously. An IR image "frame" (and time) was then obtained at the exact Az/El view angle needed by stepping through the IR movie clips. For each image an "area of interest" was then drawn around the target's perimeter to obtain target-only IR signature. SIMIR IR signature predictions from target-state data were performed at that exact frame time, range, and imager waveband. A total of 140 such "prediction-vs-measurement" points were needed to cover the 104 IR spec points due to plume spectral-contamination effects (an additional 42 and 44 validation points were performed for the additional AFOTEC flight conditions and plume-specific model validation, respectively).
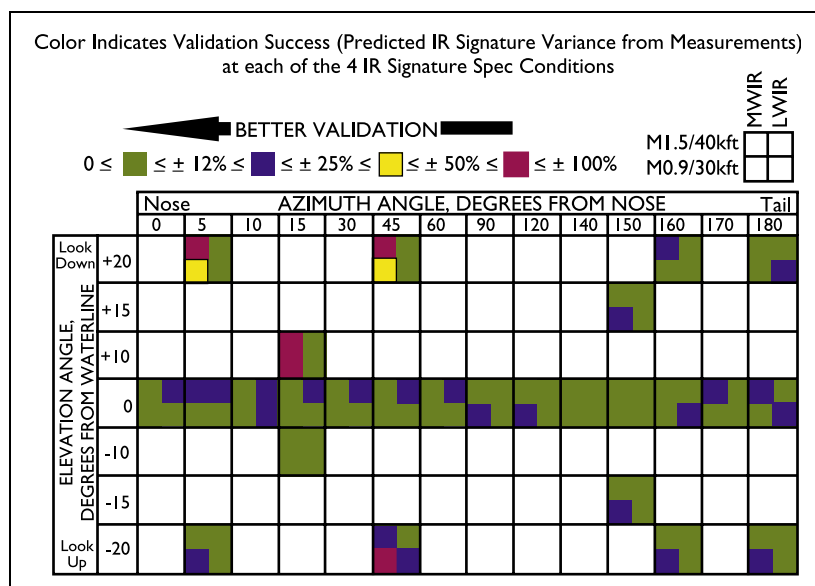
Figure 5. F/A–22 IR Signature Model Validation Results

IR Model Validation

Figure 5 (as shown on page 12) shows the results of IR model validation over the 104 IR spec points (2 flight conditions; 2 wavebands; 26 Az/El view angles). Overall, the F/A–22 IR model quite successfully predicted flight test target-only radiant intensity measurements once F119 component surface temperature prediction methodology was revised. Seventy-three of the 104 points were within +/-12% agreement, which translates to within about six percent in detection range. All but seven of the 104 points shown in Figure 5 fell within the +/-25 percent ("within +/-1 dB") validation acceptance criteria (shown in blue or green). Six of these were due to temperature over predictions of the Primary Heat Exchanger (PHX) screen (affecting look-down views in the front sector in the MWIR) and one was due to an unavoidable near-solar-specular view angle during flight testing. All LWIR points were within the +/-25 percent validation criteria. Given that all seven "yellow and red" points were over predictions (i.e., the measured signature was less than predicted) and consequently posed no spec compliance risk, the customer agreed not to spend budget/schedule improving these aspects of the IR model (better PHX screen temp prediction and improved MWIR IR top-coat reflectance data). The end result of the IR model validation process is a validation factor, which is simply the numerical percentage variance of predictions from measurements associated with each colored block in Figure 5.

IR Specification Compliance

Having completed IR flight testing and model validation (i.e., arrived at the validation factors), IR model predictions are then made at the exact (environment, waveband, flight conditions, etc.) conditions of the IR specification (termed: uncorrected Status signature). The flight-test-derived validation factors are then applied to each of the 104 uncorrected Status signature predictions to produce corrected Status signature. With varying degrees of margin, all corrected Status signature predictions were within their respective IR specification levels. In addition to demonstrating IR spec compliance the now validated model has been, or will be, used to—

1. Predict air- and ground-based IR threat missile lock-on and Acquisition Sensor (IRST) detection ranges

2. Provide data for IR countermeasure system performance assessment (effectiveness and sizing)

3. Supply data to System Effectiveness models and Simulators

4. Evaluate future signature reduction options

5. Mission planning

Conclusions

F/A–22 IR signature flight testing produced a substantial amount of high-quality calibrated IR imagery at tactically relevant conditions. This rigorously conducted validation process has resulted in a high fidelity IR signature model of the F/A–22, whose accuracy confidence has been quantifiably substantiated via high-quality flight test data. It is believed the comprehensiveness of these in-flight IR measurements and the related IR model validation activities are unparalleled for any tactical aircraft in known DoD history. ∎

Jim Cline, Denny Behm, and Karen Kidd are Signature Integration Engineers at Lockheed Martin Aeronautics Company-Fort Worth, Kevin Young leads the ATIMS IR Pod Measurement Group at the Naval Air Warfare Center, Point Mugu, California.

JASPO/NASA Cooperate

to Improve Commercial Aviation Security

■ by Charles Pedriani

The National Aeronautics and Space Administration (NASA) Aviation Safety and Security Program Office announced its Aviation Security Project at a rollout workshop in March 2003. The project represents the culmination of technology demonstrations and planning to examine the role of NASA in bolstering the security of commercial aviation. The broad goal of the program is to apply NASA's unique resources in developing technologies to address security needs in future air transportation. NASA is uniquely qualified to apply advanced technologies that can enable a new paradigm for aviation safety, security, and capacity. NASA's long-range research and development (R&D) capabilities provide the underpinning for technologies transferred into new security products for both civilian and military aviation.

This ambitious program involves a wide breath of technologies and represents a fundamental change of paradigm regarding security of the commercial aviation.

Since many of the technologies being evaluated are relatively new to NASA, help from other government agencies and contractors is being sought. DoD is expected to be of particular help in the aircraft hardening efforts such as structural hardening, Electromagnetic Interference (EMI) protection, Man-Portable Air Defense Systems (MANPADS) protection and fire prevention from security threats. JASPO has been facilitating this cooperation by fostering participation within the JASPO activities and by identifying other DoD research and development efforts involving technology of interest.

Overview of the NASA Aviation Security Initiative

A systems approach will be used as shown in Figure 1. The total risk of exposure will be reduced by first understanding individual system and "system of systems" vulnerabilities and then reducing or eliminating these vulnerabilities where possible. In cases where it is not possible to eliminate the vulnerability, measures will be taken to prevent the vulnerability from being exploited. Finally, in cases where it is not possible to eliminate exploitation, the consequences of the exploitation will be minimized. The goal of this process is to identify both operational concepts for security and advanced technology requirements.

The layered approach to security includes four pillars as shown in Figure 2. Technologies will be developed to increase the effectiveness of aviation information screening at airports. Additional efforts will be aimed at hardening the National Airspace System and providing additional security and protection for the aircraft. Advanced sensors will be developed and integrated throughout the security enhancements to enable all the measures to achieve maximum effectiveness.

Aviation Information Screening

This pillar will develop technologies that enable fast and accurate methods for analyzing and assessing aviation security threats and tools for real-time management of security information. Methods will be investigated for improved knowledge discovery and data investigation for real-time identification of threats. A Threat Assessment and Response System (TARS) will be developed to assist with decision-making under uncertain situations by integrating a Logic Evolved Decision Model with the Advanced Data Integration System (ADIS). The ADIS will include a complete and current picture of the National Airspace System, such as
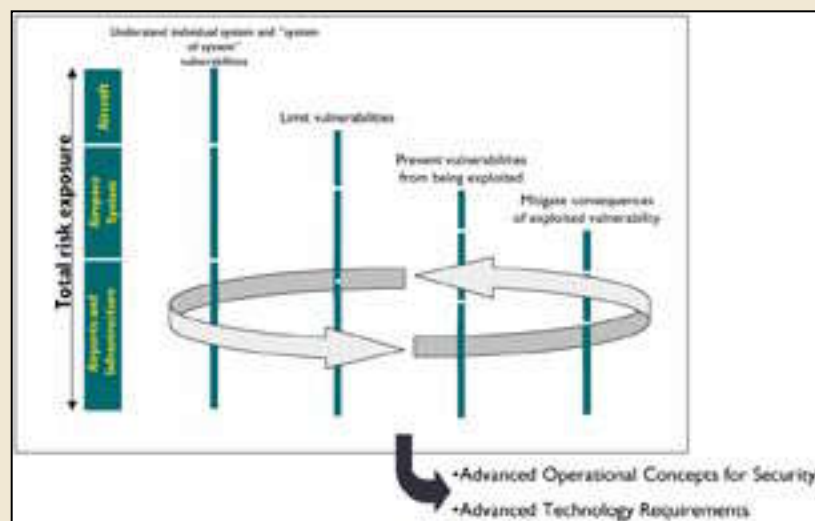

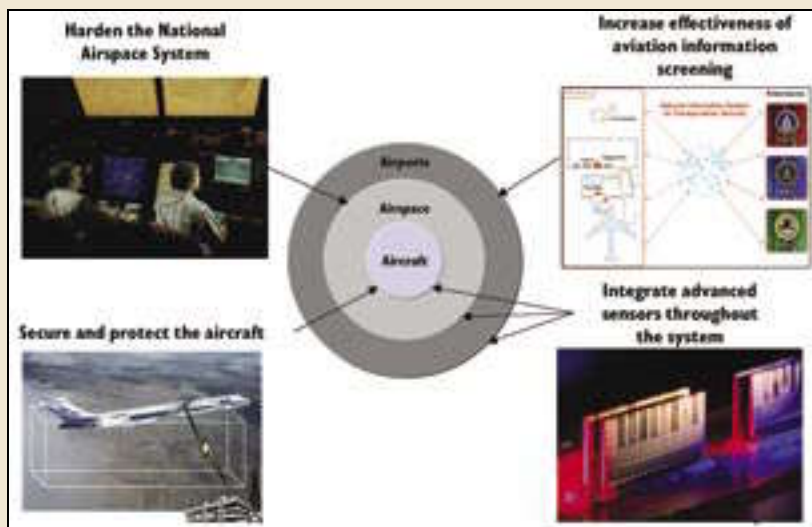Figure 1. Systems Approach to Aviation Security

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Figure 2. Approach to Aviation Security

Figure 3. Aircraft and System Hardening

flight plans, radar tracks, weather conditions, and Air Traffic Control (ATC) actions.

A Security Incidents Reporting System (SIRS) will be developed to allow dissemination and analysis of important events and to increase awareness throughout the system of potential problem areas.

In addition, technologies that may be available within NASA to assist with this activity will be identified and examined for application.

Secure Airspace Operations

This pillar will develop ground-based decision support tools to detect threatening or rogue aircraft and manage response actions. This capability will hinge on development of detection algorithms, including weather effects, and rudimentary rogue response algorithms which will have to be provided to North American Aerospace Defense Command (NORAD) and integrated into FAA systems.

Support technologies include real-time monitoring, threat recognition and reconciliation, alerting and coordination of response and resolving conflicts between airspace and threats.

Aircraft and Systems Hardening

This pillar, described in Figure 3, will develop technologies to provide passive barriers or active interdiction against threats to the aircraft and on-board systems.

Protected Area Systems technologies will be developed for the next generation aircraft to provide an alternative to current "last resort" systems. This will involve secure vehicle-based technology, automation to offset hostile human actions and prevent the use of the aircraft as a weapon of mass destruction. The approach is to develop intelligent systems to detect, alert, and counter abnormal conditions, monitor and assess pilot intent, and employ a secure flight system to minimize unauthorized use of the aircraft.

Evaluation of systems vulnerability to EMI threats will be conducted and viable mitigation options to harden digital systems will be examined. The broad goal is to protect the aircraft from the range of Electromagnetic Warfare (EW) options available. In the near term, guidance will be developed for low cost hardening options for the existing fleet. In the long run, extensive evaluations of the vulnerabilities of commercial aircraft to this threat will be conducted and technologies will be demonstrated for the next generation of aircraft.

The use of Adaptive Flight Controls to safely control and land an aircraft damaged by a MANPADS strike will be examined. A variety of technologies will be examined to demonstrate an integrated adaptive control system for the next generation of aircraft and potential interim applications or solutions for the current fleet. These technologies include detection and identification of the event, fault detection and isolation, damage and impairment identification, control reconfiguration, and upset recovery.

Research into robust high-strength, low-weight structures to provide an unprecedented resistance to both the impact of explosive forces and fire will be conducted. In addition, structural weight and cost will be impor-

tant considerations. The approach will involve the development of material systems, material forms (including metal/composite hybrids) and manufacturing methods to design integrated aircraft structural concepts. Design and analysis tools will be developed and validated to model and assess the response to an explosive event. Sub-scale structural tests will be conducted to demonstrate damage mitigation and containment concepts for threats and to develop scaling principles. Full-scale tests are also planned.

Fire protection methods will be evaluated to provide protection from intentional fuel explosion/fire and other potential fires inside the aircraft. Efforts will be directed at protecting the aircraft fuel storage and the cabin/cargo areas. The fuel storage areas will be protected by various techniques such as preventing the vapor from becoming flammable through inerting, foam fillers or fire extinguishing systems, and hardening the fuel tank structure. Cabin/cargo fires originating from bombs or accelerants will be prevented or extinguished through advanced detection or extinguishing systems. Microsensor "sniffer" arrays could be used to monitor for suspicious materials and water mist or other systems could be used to knock down the fire.

Sensors for Security Application

This pillar will concentrate on developing faster, more accurate explosive, biological and chemical detection technologies that are applicable to the aviation environment. These sensors can be used in a variety of ways to improve aviation security. There are a variety of technologies being evaluated to fill this need; however, significant improvements are needed in speed, accuracy, and ease-of-use.

The JASPO Role in Aviation Security

JASPO is serving as a focal point for technical interchange in areas of interest to NASA and has provided information about currently funded projects in response to their requests. At NASA's invitation, JASPO has attended a workshop on aircraft fire/fuel safety and security, and the NASA Aviation Security Roll Out Workshop. JASPO engineers from the Naval Air Warfare Center Aircraft Division (NAWCAD), Naval Air Warfare Center, Weapons Division (NAWCWD), and the 46th Test Wind at Wright-Patterson AFB, Ohio have collaborated with NASA on MANPADS and fire protection efforts. Primary areas of interest to NASA include structural hardening, adaptive flight controls, and fire protection. The JASPO expects to continue its dialogue with NASA in support of its aviation security initiative on a non-interference basis with its primary mission.

Mr. Charles Pedriani received his BS degree in Mechanical Engineering from Pennsylvania State University. He was involved in many aspects of Army aviation survivability improvement during his 27 years with the Army's Aviation Applied Technology Directorate. Since 1996 he has worked in a variety of assignments for SURVICE Engineering. At the current time he is providing contractor support to JASPO.

Mr. Douglas A Rohn received his M.S. in Mechanical Engineering from The University of Toledo, and Bachelors of Mechanical Engineering from Cleveland State University. During his 26 years at the NASA Glenn Research Center, he has performed research in aerospace mechanical components, including traction drives, helicopter transmissions, spacecraft mechanisms and robotics. Recently, Mr. Rohn managed projects in Aerospace Propulsion and Aviation Safety. He currently is serving as the Acting Deputy for Aviation Security Research in NASA's Aviation Safety & Security Program. He may be reached douglas.a.rohn@nasa.gov.

Figure 4. NASA Aviation Security Project: Proposed Milestones
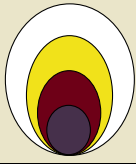
Improving Aircraft Survivability

Through Implementation of On-Board Inert Gas Generating Systems

■ by Mr. Robert J. Demidowicz

Military users, aircraft designers and manufacturers typically address the basic framework of the aircraft survivability chain during the development phase of new aircraft design or modernization programs to improve aircraft survivability. The aircraft survivability chain, illustrated in Figure 1, consists of four key links—avoid detection, avoid engagement, avoid damage, and crash worthiness.

Significant effort is made to implement the appropriate aircraft systems such that an aircrew is able to avoid being detected or engaged during mission execution. However, it is still necessary to address the "avoid damage" link of the aircraft survivability chain. It is in addressing this link where ballistic tolerance requirements are typically imposed on all major aircraft systems. When addressing ballistic tolerance of the aircraft fuel system, it is very common to see the incorporation of self-sealing fuel tank technology for both the main fuel system, as well as the adaptable and modular internal and external auxiliary fuel system kits. This is an especially crucial area in rotary wing aircraft as these aircraft are regularly employed in low altitude battlespace and are thus exposed to a significantly higher risk of enemy ground fire and atmospheric conditions, which make fuel vapors extremely volatile.

This article will describe the criticality of further addressing the survivability of an aircraft fuel system through the implementation of an On-Board Inert Gas Generating System (OBIGGS) in order to adequately address ballistic tolerance. This will include an overview of the risk, comparative review of the available survivability options for addressing aircraft vulnerability posed by the fuel system, aircraft system level parameters that drive OBIGGS sizing, and some examples of non-developmental systems available to meet the requirements of today's aircraft.

What is the risk?

Aircraft fuel systems can pose a serious and catastrophic explosion risk to the aircraft and crewmembers. The risk is significant as the high volume of fuel that is typically carried by an aircraft exposes a large portion of the aircraft to the dangers of enemy ground fire. The risk is the mixture of fuel-rich vapors and air that makes up the fuel tank ullage. The ullage is the portion of the fuel tank volume containing air and fuel vapor. The ullage continually increases in size as fuel is being consumed by the aircraft propulsion system. Through many years of research and live fire testing, it is commonly accepted that in order to mitigate the potential for a catastrophic fuel tank ullage explosion, it is necessary to reduce the oxygen concentration from the 21 percent that is present in a standard volume of air to 9.8 percent at sea level when inerting fuel tank ullages with nitrogen gas. This provides the aircraft and its crew with the necessary protection from an enemy threat of up to and including 23-–millimeter high explosive incendiary rounds. Additional factors, including temperature and the partial pressure of the oxygen based on atmospheric altitude, play a role in determining when the actual oxygen-rich fuel vapor ullage is considered explosive. Typically, inerting systems are designed to lower the oxygen concentration in the fuel tank ullage cavity to 9 percent in order to provide adequate protection with an appropriate safety margin over the 9.8 percent requirement previously discussed.

How do we address the risk?

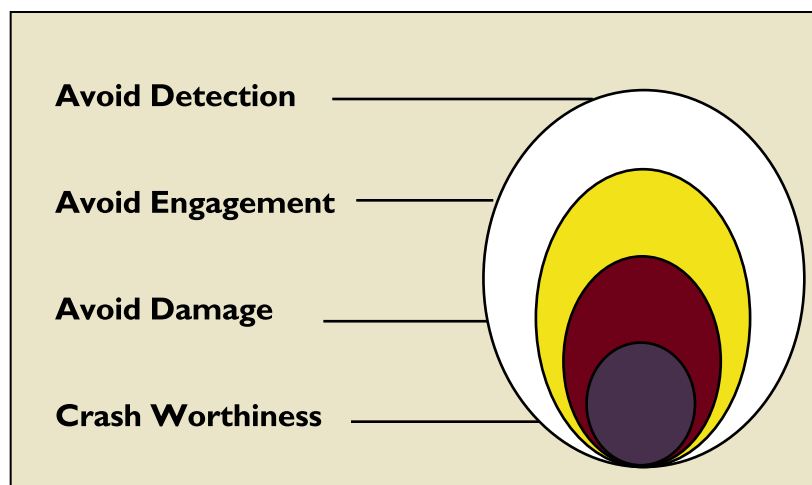Ballistic protection for the aircraft fuel system is always a major design

Figure 1. The Aircraft Survivability Chain

- Avoid Detection
- Avoid Engagement
- Avoid Damage
- Crash Worthiness

issue when addressing aircraft survivability. As discussed earlier, fuel tank ballistic protection is typically addressed through the incorporation of self-sealing, ballistically tolerant fuel cells. The key is incorporating a system that is complimentary to self-sealing fuel cells, while at the same time providing the necessary protection against the possibility of a fuel tank explosion against everything from environmental threats, up to and including 23–millimeter enemy ground fire. The options that are usually discussed and outlined below are reticulated foam, liquid nitrogen, HALON, and OBIGGS.

Reticulated Foam. In this particular approach, porous foam is installed into the fuel cell. The ability to cut the foam makes this approach flexible in meeting the requirements of any peculiar sized fuel cell. However, there are some considerable drawbacks associated with the installation of foam. The most commonly known are those of reduced fuel tank volume, approximately three percent, and substantial weight penalty. In a military transport/cargo aircraft it is not uncommon for a foam solution to add upwards of 1,000 pounds to the aircraft. Even in a rotary wing application system, weights could reach 100 pounds. The maintenance impact is not as commonly known but is a major consideration to incorporating this approach. Typically, the foam needs to be removed from the fuel cells in order to conduct standard fuel system repairs. Additionally, the foam needs to be bagged or contained as it is considered a hazardous material once it has been exposed to fuel. This can have a major impact when working on a large aircraft that may be equipped with foam. Another potential effect of some types of reticulated foam, is the possibility of fuel system contamination attributed to the deterioration and breakdown of the foam.

Liquid Nitrogen. The incorporation of a liquid nitrogen system may provide a weight savings of approximately 500 pounds less than foam that may initially be attractive. However, safety and logistical issues quickly come to bear on this approach. A critical area of concern

is that liquid nitrogen is a cryogenic agent and poses a safety issue to the maintenance and support crew during the refilling process. It is also stored at high pressure, typically 400 psig, and thus poses an aircraft level explosive safety concern. Logistics is a major issue as the liquid nitrogen system needs to be checked periodically as well as refilled after each mission use and/or if the system is in a fully charged state and the gas is boiling off as a result of the actual liquid to gaseous conversion process itself. This refilling process requires extensive facility capability, or reachback, if the aircraft is deployed into an area which does not have an established liquid nitrogen infrastructure. A gaseous nitrogen solution would require significantly more storage volume than a liquid solution, and is stored at a much higher pressure, approximately 2,000 pound per square inch gauge (psig). Both liquid and gaseous nitrogen systems may also pose a crewmember threat from excessive leakage and related oxygen deficiency in some aircraft applications. Finally, enough liquid or gaseous nitrogen is only typically available to provide protection for a single mission and specifically when only entering the combat area.

Halon. Providing protection utilizing a Halon gas brings similar logistical issues of maintenance checks and refilling after utilizing the agent to protect the crew during the combat phase of a mission. The 1987 Montreal Protocol has also banned the use of Halon due to its destructive effects on the earth's ozone layer. Significant research continues in the area of new chemical formulations which are not ozone depleting and can be utilized as aircraft fire extinguishing or suppression protection systems. Initial research is focusing on the weight and effectiveness deficiencies of new agents as compared with the agents banned under the 1987 Montreal Protocol.

On-Board Inert Gas Generating System (OBIGGS). This method of full-time inert gas generation is typically provided by either molecular sieve or hollow fiber membrane based systems. These OBIGGS systems utilize cooled engine bleed air

as the air source and then, separates the inlet air into a nitrogen-enriched product air stream and a slightly oxygen-enriched vent stream (through a physical and not chemical based process). The vent stream is then routed either overboard or into an unpressurized bay to maximize the effectiveness of the OBIGGS system.

The OBIGGS approach has significant advantages in that it will provide an aircraft fuel system with a continuous and unlimited supply of nitrogen gas and there are virtually no maintenance related activities required. The only maintenance activity that is associated with an OBIGGS system is the occasional replacement of an inlet air filter, approximately every 1,000 hours depending upon the cleanliness of the engine bleed air that is being utilized as the OBIGGS source air. The integral OBIGGS oxygen monitor provides the pilot and/or maintenance crew with notification of required maintenance actions. Repair of the actual system is typically performed by the original equipment manufacturer (OEM) as the system reliabilities for this type of system, including health monitoring, is greater than 10,000 hours mean time between failures. To give the reader a better understanding of this reliability, a user would encounter only three system failures per year, based on a 100 aircraft fleet, where the total average flight time per aircraft is 20 hours per month.

OBIGGS is a proven solution that has minimal aircraft integration impact and negligible long-term maintenance and lifecycle costs. When OBIGGS is incorporated with self-sealing fuel tanks, it will meet the survivability needs of the "Avoid Damage" link of the aircraft survivability chain, as it applies to the aircraft's fuel tanks. This includes providing protection against multiple hit scenarios.

Driving OBIGGS System Size—Aircraft System Level vs. Mission Parameters

The molecular sieve and hollow fiber membrane based OBIGGS are significantly different enough that each of them is best suited for specific types of aircraft applications. The molecu-
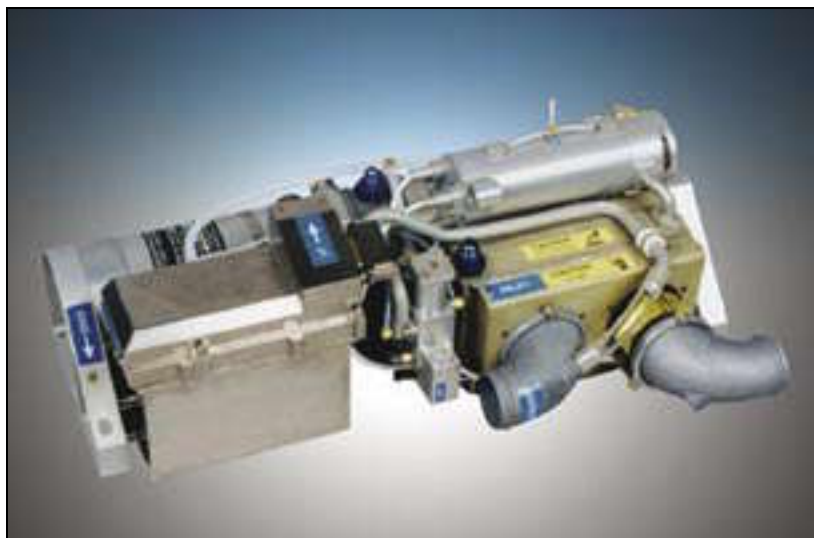
Figure 2. Attack/Combat Search and Rescue/Utility Helicopter OBIGGS

Figure 3. Cargo/Transport Helicopter OBIGGS

lar sieve has optimal performance with low pressure (typically between 10 and 40 psig) and low temperature (typically between 0 and 120 degrees F) inlet air conditions, where as hollow fiber membranes have optimal performance with high pressure (typically between 35 and 90 psig) and high temperature (typically between 160 and 200 degrees F) inlet air conditions. The hollow fiber membrane process also tends to be more air efficient as a function of input to output gas ratio. As such, the molecular sieve system approach tends to be best suited for rotary wing applications where inlet air pressures tend to be low throughout the flight profile and overall air usage is low, based on the total fuel load to be protected. However, a hollow fiber membrane system becomes very attractive in aircraft applications where higher bleed air pressures may be available and a large fuel load needs to be protected. This could provide a significant aircraft integration advantage by minimizing the total inlet air requirement as compared with a comparable molecular sieve OBIGGS.

Aircraft mission and performance requirements ultimately have a substantial impact on not only the size of the OBIGGS required, but even potentially in the type of technology that is to be used. The main parameters that typically influence OBIGGS sizing are—

1. Total fuel load to be protected,

2. Initial time-to-inert requirement.

3. Rate of ascent and descent.

4. Fuel system vent pressurization.

For instance, an aircraft that has a vent pressurization schedule of +3/-3 psid on the climb and dive side respectively, will provide a substantial benefit of smaller size for an OBIGGS required to maintain an adequate level of protection during a tactical descent mission segment. However, this same benefit may require a user to consider a compromise in meeting the initial time-to-inert requirement, as the OBIGGS needs to provide enough product gas to build up enough pressure in the fuel tank to overcome the +3 psid before oxygen rich air can be exhausted out of the fuel tank.

Overall, the sizing of an OBIGGS system for a given application requires a fair amount of trade-off analysis. This determines what is the best technology approach to meet an aircraft's mission requirements within the aircraft's available system level capabilities, and where some compromises can be made in the interest of minimizing size and weight of the OBIGGS system.

Non-developmental OBIGGS Systems Available to Protect Today's Aircraft

The ultimate test of incorporating an OBIGGS system into today's aircraft is whether or not it can be accomplished with minimal weight impact to the aircraft. The next few figures will provide the reader with an overview of systems available to meet the needs of typical rotary wing and military transport/cargo aircraft. Figure 2 illustrates an attack/combat search and rescue/utility helicopter OBIGGS system with an integrated heat exchanger and oxygen monitor. The total system weight when fully integrated into an aircraft, including plumbing and electrical wiring, is approximately 45 pounds and utilizes on average approximately one pound per minute of bleed air. Larger cargo/transport style helicopters can be protected with the OBIGGS system illustrated in Figure 3. This system has an integrated oxygen monitor and would accomplish the conditioning of the inlet bleed air through a separate heat exchanger. The total system weight for this unit when integrated into the aircraft, including plumbing, electrical wiring, and heat exchanger, is approximately 65 pounds and utilizes on average approximately two pounds per minute of bleed air. Finally, Figure 4 illustrates the type of OBIGGS system that would be utilized to meet the needs of the other end of the aviation spec-

trum, the military cargo/transport aircraft. The air separation module illustrated in Figure 4 was designed to allow a user to meet the inerting needs of their aircraft through the incorporation of multiple units, thus providing a common approach to multiple aircraft types. For a typical military cargo/transport aircraft, the total system weight, including air separation unit(s), heat exchanger, plumbing, and electrical wiring, is approximately 250 – 400 pounds. The air consumption for this type of system is approximately between 7 and 16 pounds per minute.

Summary

In summary, it is critical to properly address the catastrophic explosive risk associated with taking enemy fire into the ullage of a fuel cell. In this article it has been illustrated that there are several methods by which this can be accomplished, and thus ultimately increasing aircraft survivability. After considering all of the options and the particular integration details, aircraft level impact, and lifecycle and maintenance issues, an On-Board Inert Gas Generating System (OBIGGS) is a technically feasible and realistic solution for today's aircraft. When it comes to providing aircraft fuel system ballistic tolerance capability, it is necessary to understand that protecting from a catastrophic explosion in a fuel tank ullage cannot be accomplished solely with self-sealing fuel cells. To provide the desired level of ballistic tolerance requires a hand-in-hand complimentary approach which incorporates both self-sealing fuel cells and OBIGGS. Ultimately, it is necessary to incorporate the appropriate fuel system requirements verbiage requiring a self-sealing capability and that damage from certain high explosive incendiary and/or armor piercing incendiary rounds must not cause catastrophic explosion. This will drive a solution, which provides the proper level of survivability protection for both permanently mounted and auxiliary internal fuel cells.

Robert J. Demidowicz currently leads all OBIGGS Business Development activities for Carleton Life Support Systems, Inc., in Davenport, Iowa. He is actively involved in the American Institute of Aeronautics and Astronautics and holds B.S. and M.S. degrees in Aerospace Engineering from Boston University.

Figure 4. Modular OBIGGS for military cargo/transport aircraft

FY04 Joint Aircraft Survivability Program

■ by James Buckner

As we start out fiscal year 2004, the Joint Aircraft Survivability Program Office (JASPO) will fund 44 new projects and continue funding to completion three Group projects, three Survivability Assessment projects, four Vulnerability Reduction projects, five Susceptibility Reduction projects and six Joint Live Fire Air Test projects, in addition to supporting the Central Office overhead.

A short description of the projects approved for funding and recognition of the JASPO members who are doing the work is given below.

Susceptibility Reduction

In FY04, the Susceptibility Reduction Subgroup (SRSG) will complete five projects started in prior years. The first is the UAV Active Acoustic Cancellation Project, under the guidance of Mr. Jim Young at NAWCAD, Pax River. The objective of this project is to develop radiation patterns and spectral content of acoustic emissions from push/pull propeller driven UAVs and then determine passive and active signature reduction techniques.

Also to be completed is the Imaging Seeker Aim Point project, under Richard Moore at NRL. The contractor is Georgia Tech Research Institute (GTRI). The objective is to determine how to counter an imaging infrared seeker in threat missiles.

Special Materials Aero Urban Decoy (SMAUD) project, under Mr. William Taylor at the Air Force Research Laboratory (AFRL) will also be completed. The contractor on this project is Alloy Surfaces, Inc. This government/industry team will develop an aerodynamically stable SMAUD which is reliable, economical, and safe for deployment at low altitude environments and can protect low flying large fixed wing aircraft. It will be inexpensive to produce (less than $150 per unit) and be capable of being dispensed from current operational dispensers.

Another project the SRSG will be continuing in FY04, and scheduled for completion in FY05, is the High Power Wideband Array project. Started by Dr. Stephen Schneider, the project is being picked up by Dan Janning at AFRL. It will develop and fabricate a wide band aperture array capable of transmitting high power (over 2–18 GHz). The wide bandwidth of operation would allow several jamming systems to be combined into one aperture, resulting a decrease in weight and space requirements, as well as a reduction in the cost of ownership to Navy and Air Force combat and support aircraft.

Also continuing in FY04 and scheduled for completion in FY05 is the Laser-Focal Plane Array (FPA) Effects Modeling for Laser Countermeasures Optimization project. This project is headed by John Keat at AMCOM. Mike Porter of Dynetics, Inc. is the contractor. This effort will develop a multi-physics model allowing quantitative studies of the interaction of the short-pulse laser pulses and allow laser IRCM developers to optimize the laser operating parameters in order to more fully exploit FPA detector technology.

There are eleven new starts for FY04 within the Susceptibility Reduction Subgroup. These are:

1. **Common Service Exciter.** Chris Moss at NRL—Anthony White and George Gonczy at WPAFB, OH (start in FY04 finish in FY06)

2. **Countermeasure Susceptibility of Several New Foreign IR Threat Seekers**—Richard Moore at NRL, E. Huber at WPAFB and Al Boyd at MSIC (start in FY04 finish in FY06)

3. **Reactive IR Suppressor (Feasibility Study)**—Kelly Unsworth at AATD (start in FY04 finish in FY06)

4. **Impact of Electronic Limiting on Imaging Seeker Countermeasures**—Richard Moore at NRL and John Keat at Redstone (start in FY04 finish in FY06)

5. **Low Cost Commercial Off-the-Shelf (COTS) based pointer tracker for helicopter IRCM**—John Winter at Ft. Monmouth, and Michael Scott. Contract support will be provided by Chuck Miyake of Aculight Corp. (start in FY04 finish in FY06);

6. **Affordable Visible Missile Warning**—John McCalmont, Ph.D., Richard Sanderson, Ph.D. and William Taylor from WPAFB, OH (start in FY04 finish in FY06)

7. **Derivative Russian MAN-PADS IRCM**—Chris Keane and Allan Chan at CECOM (start in FY04 finish in FY05)

8. **High Resolution IRCM Measurements**—Mark Nosek

at WPAFB and Richard Moore at NRL (start in FY04 finish in FY06)

9. **Millimeterwave Electonic Warfare UAV Stand-in-Jammer Receiver**—Christian Hochuli and Chris Moss at NRL (start in FY04 finish in FY06)

10. **Miniaturized Countermeasures for UAVs**—Jim Young at NAWCAD and Penny Bott at NAWCWD (start in FY04 finish in FY05)

11. **Susceptibility Reduction Strategic Planning**—Frank Barone, Ph.D. at NRL, Tony White at WPAFB and Mike Scott at Fort Monmouth

Vulnerability Reduction

In FY04, the Vulnerability Reduction Subgroup (SRSG) will complete four projects started in prior years. The first is the MANPADS Impact Point Assessment project headed by Mr. Greg Czarnecki from the 46th Test Wing at WPAFB with an assist from Mr. Al Boyd (MSIC, Redstone Arsenal), Mr. David Payne (STRICOM, Redstone Arsenal), Mr. Gary Johnson (White Sands Missile Range), Mr. David Edwards (46th Test Wing at Eglin AFB), and Mr. Terry Dougherty (NAWCWD). The objective of this project is to validate the ability of MANPADS fly-out/endgame M&S methodologies to discriminate between adjacent IR targets and predict hit points.

The next is the Bonded Wing Survivability Demonstration project. This is a co-operative program being funded by the JASPO and Bell Helicopter Textron, Inc (approximately 50-50 percent). Mr. Nicholas Calapodas of the Army Aviation Applied Technology Directorate (AATD) at Fort Eustis is the project engineer on this project which will fabricate a section of the V–22 wing using bonded composites technology to co-cured skin/stiffeners and bonded wing ribs. The project will conduct ballistic and structural post-ballistic testing. The program is derived from the recently concluded Design and Manufacture of Low Cost Composites-Bonded Wing (DMLCC) program, which was also jointly sponsored by Bell Helicopter Textron and the Government. A 24–feet V–22 wing section has been designed and manufactured, and it successfully underwent static and fatigue testing.

The objective of the FY04 program is to demonstrate the structure's ballistic survivability. Nick Calapodas is also in charge of the Advanced Survivable Rotorcraft Validation project and is assisted by Greg Czarnecki and Dave Barrett. The first objective of this effort is to enhance the technology base to design hardened rotorcraft structures against large ballistic threats—to include MANPADS—and remain within acceptable weight and cost requirements. The next objective is to validate a low cost/weight MANPADS hit-point biasing concept. In the first case, ballistic testing is highly desirable and in the second MANPADS testing is mandatory. The JASPO anticipates that the Joint Live Fire program will assist with the performance of this program. Participating contractors are Bell Helicopters, Boeing Helicopters and Sikorsky Aircraft (Rotary Industry Technology Association).

The Rotary Wing Aircraft Battle Damage Repair—Study of Repair Effectiveness and Durability project is continuing this year and is expected to be completed in FY06. It is headed by Mr. Robert L. Laughman at the Army Evaluation Center (AEC) and supported by Mr. Richard Jackson at the Army Aviation Logistics School. Contractors are SURVICE Engineering Company and the Boeing company. The objective is to examine 2–3 primary Army Aircraft Battle Damage Repair techniques for the longevity under flight loading/ flight conditions to establish the length of time the repair technique can be expected to perform in operational flight hours.

The MANPADS Damage Effects Modeling effort was started in FY03 and is expected to be completed in FY05. Managed by Alex Kurtz from the 46th Test Wing this project will develop a physics based methodology to predict synergistic MANPADS damage effects from kinetic energy and warhead detonations.

There are twelve new starts for FY04 within the Vulnerability Reduction Subgroup. These are:

1. **Enhanced Powder Panels**—(Start and finish in FY04)

2. **Auto Engine Suppression System (Phase I – Plan)**—Bill Leach and Marco Tedeschi at NAWC Lakehurst and Joe Dolinar at NAWCAD (Start of FY04 and finish in FY06)

3. **RPG Modeling & Simulation DYTRAN 3D (Based on JLF RPG Testing)**—Robert Laughman and Robert Wojciechowski at USAEC, Aberdeen (start in FY04 finish in FY06)

4. **Joint Resistance to RAM**—Greg Czarnecki at 46th Test Wing (start in FY04 finish in FY05)

5. **Intumescent "Instant Firewall"**—Peggy Wagner at 46th Test Wing (start and finish in FY04)

6. **Assessment of Tank Wall Pressures for ERAM Validation**—Peggy Wagner at 46th Test Wing (start and finish in FY04)

7. **MANPADS Damage Effects on Large Aircraft Engine**—Greg Czarnecki at 46th Test Wing (start in FY04 and finish in FY06)

8. **SECAD Methodology on Turbo-shaft and High-Bypass Ratio Engines**—Chuck Frankenberger at NAWCWD (start in FY04 and finish in FY06)

9. **Complex Composite Rotorcraft Structures Survivability**—David Friedmann at AATD (start in FY04 and finish in FY05

10. **Follow-on Issues for Weapons Bays**—Marty Krammer and Leo Budd at NAWCWD, Alex

Kurtz at 46th Test Wing (start and finish in FY04)

11. **Effects on Aircraft Structure Resulting from Ballistic Impact to Flare Buckets**—Rimi Rivera and Tim Hutchison at NAWCAD and Joe Manchor at NAWCWD (start in FY04 and finish in FY05)

12. **UAV Survivability Enhancement Techniques**—Kevin Nolan at AATD and Pat O'Connell at 46th Test Wing (start in FY04 and finish in FY06)

Survivability Assessment

In FY04, the Survivability Assessment Subgroup (SASG) will complete three projects started in prior years.

Mr. Martin Lentz from the 46th Test wing at WPAFB is the responsible engineer for the DBFM/WINFIRE Model Enhancements project. The objective of this project is to develop and maintain, together with the JTCG/ME, a standard dry bay fire model and a fuel tank ullage explosion model for stand-alone analysis and future insertion into the AJEM. The DBFM/WINFIRE model will provide the framework to enable modeling of physical threat/target interactions that cannot be done within current models such as hydrodynamic ram filling the dry bay, fire pooling and spread, airflow within the dry bay with clutter, time dependent damage, and synergistic effects.

DREAM is the Directed Radio Frequency (RF) Energy Assessment Model. The DREAM Verification for Entry into SURVIAC project is to perform initial verification and validation (V&V) of the model sufficient to enter it into SURVIAC as a category 2 model.

The Modeling & Simulation (M&S) Requirements project will document the short- and long-term survivability related analysis requirements of the Joint survivability community. This task is headed by Ron Ketcham, NAWCWD, China Lake, with assist from Lex Morrissey at ARL and Marty Lentz at the 46th Test Wing.

Seven other projects started in prior years and continuing past FY04 are:

The SURVIAC Model and Simulation (M&S) Accreditation Support Information project under Ms Michelle Kilikauskas at NAWCWD provides a credibility assessment of the models and simulations, which are distributed by SURVIAC and are documented in the form of standard Accreditation Support Packages (ASP's). ASPs are a three volume set of documentation which provides: (1) a Model Status Overview, (2) a Functional Characterization, and (3) Detailed Verification and Validation (V&V) results. By establishing accreditation support data in the standard ASP format, new model users who have unique requirements can add to the body of knowledge about the model by simply adding change pages to the ASP reports. This effort started in FY02 and is expected to continue to FY06.

Mike Wesienbach from the JASPO and Ron Ketcham, JASPO's Survivability Assessment Subgroup Chairman, oversee the SURVIAC Model Manager Support project. The objective of this effort is to provide model manager support for the JASPO models in SURVIAC. They are: Enhanced Surface-to-Air Missile Simulation (ESAMS), Air-to-Air Combat Models, Advanced Low Altitude Radar Model (ALARM), Radar Directed Gun Simulation (RADGUNS), Advanced Joint Effectiveness Model (AJEM), the fly-out model BLUEMAX IV, Directed RF Energy Assessment Model (DREAM), Computation of Vulnerable Areas and Repair Time (COVART), Fast Shot-line Generator (FASTGEN), and in the near future the Joint Threat Engagement Analysis Model (JTEAM). The Model Deficiency Report (MDR) process will be maintained and model users will be promptly advised of software changes for their version of each SURVIAC model. SURVIAC is the Survivability Information Analysis Center managed under contract by Booz Allen and Hamilton, Inc. This effort started in FY02 and is expected to continue to FY06.

Mr. Kelly Kennedy with the Aeronautical Systems Center (ASC) at WPAFB is in charge of the COVART/FASTGEN CCB project. This project performs on-going maintenance and miscellaneous support for users and those developing test cases for COVART and AJEM test cases comparisons. These are models used to generate target vulnerability data. Codes are used for either weapon system vulnerability or lethality. JLF and LFT&E predictions are also required. Ketron, Division of BIONETICS, is the contractor on this effort. This effort started in FY02 and is expected to continue to FY06.

The FPM/WINFIRE Model Enhancements project will provide survivability and lethality analysts with the ability to accurately model threat/safety induced dry bay fires in a timely manner and provide credible fire/explosion prediction capability. This project started in FY02 and is expected to be completed in FY06. It is managed by Martin Lentz at the 46th Test wing and is under contract to SURVIAC, Survice engineering Co., and Enthalpy Corp. This effort started in FY02 and is expected to continue to FY06.

Mr. Roy Randolph of NAWCWD is the lead on the Integrated Survivability Analysis project with SURVIAC support. The objective is to develop an Integrated Survivability Assessment (ISA) process for DOT&E applications. The process will combine survivability operational test and evaluation (OT&E) with Live Fire Test and Evaluation (LFT&E) results to provide an overall survivability assessment of a system under test. The approach will integrate the proper roles of modeling and simulation (M&S) with test and evaluation (T&E). The effort started in FY03 and is expected to be completed in FY05.

There are eight new starts for FY04 within the Survivability Assessment Subgroup. These are:

1. **Update Pedigree Gun and Missile Books**—Kelly Kennedy at ASC (start and finish in FY04)

2. **Simulink Environment and Tools for Advanced IR Seeker Susceptibility**—Rick Moore at NRL and Mark Nosek at WPAFB (start in FY04 and finish in FY06)

3. **COVART Modularization**—Kelly Kennedy at ASC (start and finish in FY04)

4. **ISA Demonstration**—MMA Ron Ketcham at NAWCWD (start in FY04 and finish in FY05)

5. **ESAMS Migration**—James Begovich at WPAFB (start and finish in FY04)

6. **ESAMS Validation**—Ron Ketcham at NAWCWD (start in FY04 and finish in FY06)

7. **Fault Tree Visualization and Integration**—Kelly Kennedy at ASC (start in FY04 and finish in FY05)

Group Projects

Group projects are funding six in FY04.

The JASPO Magazine *Aircraft Survivability* project under CDR Andy Cibula, JASPO Program Manager, provides the resources necessary to publish this magazine.

The Joint Combat Assessment Team (JCAT), which is a name change from the Joint-Service Air Defense Lethality Program, is a unique project utilizing both Air Force and Navy reserve personnel. The objective of the project is to develop the capability to send uniformed personnel into the field to capture combat damage data and document the damage so that it can be put in SURVIAC and be available for data reduction and analysis by the community. The Air Force portion of the program is headed up by LtCol Anthony Brindisi, USAFR. LtCol Brindisi's unit is stationed with the 46th Test Wing at WPAFB. Mr. Ken Goff's survivability division at NAWCAD oversees the Navy portion of the program. The Army portion of the program is under the oversight of Steve Polyak at ARL.

The AFIT Survivability Short Course project was created to develop and conduct a survivability short course at AFIT to replace the course originally developed and presented at the Naval Postgraduate School, Monterey California by Professor Robert E. Ball. It is expected that the first AFIT short course will be conducted in FY04 and, if successful, it will be a continuing annual course offered to government and industry.

Three other new start group projects which are still in the formulation stage are the SIRMAN–SIPRNET IR MANPADS Site, the MANPADS IPT project and the Threat Film Update project.

Aircraft Testing

The description for the Joint Live Fire–Aircraft Systems (JLF–Air) funded projects for FY04 can be found in another article in this issue of Aircraft Survivability. The article is titled, Joint Live Fire–Aircraft Systems Program (JLF–Air). ∎

Mr. Jim Buckner received a B.S. degree in Naval Science from the U.S. Naval Academy and a M.B.A. degree from National University in San Diego, California. After his service in the Navy he spent four years with Armament Systems, Inc. In 1981 he became the support contractor to JASPO.

The F–35 LFT&E Program Update

■ by Mr. Jim Rhoads

I n the Fall 2002 Issue of Aircraft Survivability, we outlined the Lockheed Martin (LM) Joint Strike Fighter (F–35) Live Fire Test (LFT) Program and promised updates as the test program matured. As we successfully closed out our Preliminary Design Review (PDR) and head toward our first Critical Design Review (CDR) in the spring of 2004, we felt it was time to provide a status of where we stand with our program. With a team comprised of Lockheed Martin (LM), Northrop Grumman (NGC), 46th Test Wing, and Naval Air Warfare Center (NAWC) – China Lake test engineers supported by technical experts from Pratt & Whitney, British Aerospace, Rolls Royce, and the Director of Operational Test and Evaluation (DOT&E), we will complete 15 Live Fire Test programs by November 2003 with six more by April 2004. LM and its team have completed new types of tests, data collection, and built innovative test articles to help achieve its goals. Several key lessons learned have already been identified and are being implemented in future tests.

The F–35 Live Fire program started with a bang in July 2002—eight months before the F–35 Air System PDR! The F–35 Live Fire Test schedule emphasized testing early in the program in order to provide design information for various systems on the aircraft. The goal was to test all critical areas prior to the first CDR. Areas of interest include —fuel ingestion, dry bay fire extinguishing, unique components on the Short Takeoff and Vertical Landing (STOVL) variant, areas identified for additional vulnerability reduction, and verification of vulnerability reduction features already on the aircraft. With only 30 months from contract award to the first Air System CDR, a significant challenge was presented to the team.

Figures 1–7 (pages 23, 26–27) highlight several test programs completed during the initial stages of testing. Figure 1 shows a frame from a video of a fuel ingestion suppression concept developed for the F–35 aircraft. This testing was conducted at NAWC China Lake using a modified F–18 test article. A new fluid leakage measuring system was developed to provide a detailed time history of the fluid leaking from the concepts tested. The final concept chosen not only met the design requirement, but also was so successful that a significant fuel savings was achieved for the aircraft.

Figure 2 is a picture from a high-speed video of the spall produced after ballistic impact to an acrylic canopy panel at the 46th Test Wing Wright Patterson Air Force Base (WPAFB). The Live Fire team supported a trade study to determine if the canopy material should be acrylic or polycarbonate. After a test series to characterize the spall material produced by the various canopy materials, the acrylic panel was endorsed. The measured spall did not have sufficient energy to penetrate the flight suit worn by a mannequin during the tests.

Figure 3 shows a picture of a Man Portable Air Defense System (MANPADS) characterization test performed at NAWC China Lake. A series of static and dynamic tests were performed using a single class of MANPADS to develop detailed data
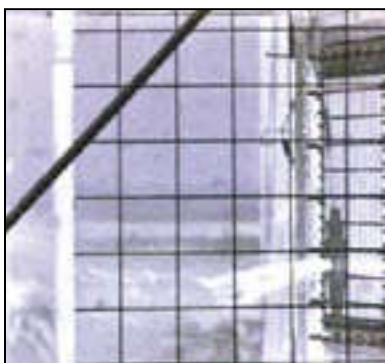
Figure 1. Quick Dump Fuel Ingestion Captured During Testing

Figure 2. Canopy Spall Produced After Fragment Impact

Figure 3. MANPADS Static Pressure Test

James E. Rhoads

Young Engineers in Survivability

■ by Dale B. Atkinson

The Joint Aircraft Survivability Program Office (JASPO) is pleased to recognize Mr. James (Jim) E. Rhoads as our next Young Engineer in Survivability. Mr. Rhoads is responsible for developing and leading the Live Fire Test and Evaluation (LFT&E) for the Lockheed Martin Joint Strike Fighter (F–35) program

Mr. Rhoads graduated from Pennsylvania State University in 1990 with a B.S. in Aerospace Engineering with an emphasis on aeronautics and aircraft design. He wrote an undergraduate thesis on the development of a new wing design which consisted of pretest predictions, construction of the wing, followed by actual wind tunnel testing. This work and all his computer courses certainly helped prepare him for the different jobs he has held, especially his current one working on the F–35.

After graduation, Mr. Rhoads went to work at the SURVICE Engineering Company in Aberdeen, Maryland as an engineer and analyst responsible for the management of vulnerability assessment programs, including writing proposals, drafting statements of work, assigning work, tracking hours and costs, marketing new tasks, and ensuring that scheduled deliverables were completed on time and on budget. His primary responsibilities included performing vulnerability analyses using manual and computer methods including the COVART, HEVART and HEIVAM vulnerability assessment models and hydro-code models. Jim became proficient in building geometric target descriptions in the BRL–CAD and FASTGEN formats and developing component probability of kill values for various types of vehicles and components. He completed various tasks for the Joint Live Fire Program and various Army Live Fire Test & Evaluation Programs, including ballistic test predictions, data collection and analysis during his time at SURVICE.

In 1997, Jim went to work for the Lockheed Martin Aeronautics Company in Fort Worth, Texas where he was responsible for performing day-to-day vulnerability support for the Lockheed Martin Joint Strike Fighter (JSF) program. Jim's duties included interfacing with designers, attending design reviews and providing vulnerability impacts for all design trades. He developed and integrated several vulnerability reduction features into the air system design and received several special recognition awards for

weight reduction efforts on the program as well as having a patent pending on one of the features. Jim also developed routing schemes that were accepted as part of the design and identified errors in the JSF configuration which he worked with the designers to resolve. Jim developed the Live Fire Test plan for the JSF aircraft and planned the test events for the Engineering, Manufacturing and Development (EMD) phase of the program. He developed inputs and analysis for the JSF EMD proposal effort and authored sections of the proposal. Jim also gained experience in chemical, biological and directed energy threats during this time.

In January 2001, Jim decided to return to the east coast, where he went to work for Applied Research Associates (ARA) in Aberdeen, Maryland. At ARA, he was responsible for conducting vulnerability assessments on ground and air vehicle targets using the MUVES and Advanced Joint Effectiveness Model (AJEM) vulnerability codes. Jim led ARA's AJEM tasks providing both technical and management oversight. These tasks included addressing Model Deficiency Reports (MDRs) submitted on the AJEM code, assigning the critical MDRs to fix, beta testing the AJEM code, and leading an effort to incorporate additional capabilities within AJEM. He was also responsible for tracking budgets and schedules as well as writing reports on these efforts.

In December 2001, Jim was asked to return to Lockheed at the Lockheed Martin Management and Data Systems Company in King of Prussia, Pennsylvania, where he is responsible for developing and leading the Lockheed Martin F–35 Live Fire Test and Evaluation program. Jim's duties include interfacing with designers, attending design reviews and providing vulnerability impacts for all design trades. He has also conducted vulnerability trade studies to reduce the JSF vulnerability and developed and integrated several vulnerability reduction features into the air system design. Jim is responsible for interfacing with government test facilities to coordinate test activities and plan ballistic test events as well as developing test plans and pretest predictions and conducting ballistic test events. He writes quick look briefings and test reports for each test event and coordinates LFT&E activities with DOT&E, and other government agencies. According to those connected to the F–35 program, Jim is doing an outstanding job and is well respected by the government engineers and oth-

ers that he is working with on this program. Jim recently received an award from Lockheed Martin in recognition of his excellent work on the F–35 LFT&E Program.

It is with great pleasure that the JASPO presents Mr. James (Jim) E. Rhoads as our latest Young Engineer in Survivability. ■

Mr. Dale Atkinson is a consultant on the aircraft combat surviv-ability area. He retired from the Office of Secretary of Defense in 1992 after 34 years of government service and remains active in the survivability community. Mr. Atkinson played a major role in establishing survivability as a design discipline and was a charter member of the tri-Service JASPO. He was also one of the found-ers of the DoD-sponsored SURVIAC. He may be reached at jasnewsletter@jcs.mil.

Figure 1: Mr. James (Jim) E. Rhoads, our latest Young Engineer in Survivability, in from of the JSF "Iron Bird" at WPAFB, Ohio.

to support Modeling and Simulation (M&S) activities. These tests included static and dynamic pressure field tests, static and dynamic fragment arena tests, and dynamic penetration tests. At the conclusion of the test series, it was widely agreed that this is how all MANPADS missiles need to be characterized in the future. Special thanks go to Bell Helicopter, Fort Worth, Texas for contributing instrumentation funding for these tests.

A new hydrodynamic ram mitigation technique to defeat a High Explosive Incendiary (HEI) projectile was tested at NAWC China Lake and is shown in Figure 4. Although the initial test data did not show appreciable attenuation, all within the test team see promise in this concept. Additional testing using the 46th Test Wing ram air gun is likely to continue on a smaller scale.

Figures 5 and 6 show pictures of tests done to some of the unique STOVL components of the F–35 variant. The good news from these tests is that the STOVL components tested to date have been more resilient to battle damage than predicted. Design data is being shared with the propulsion system team for future design improvements. A key finding of the propulsion system tests is that the aircraft's sensors need to provide the pilot with early indications of damage in order to prevent the pilot from executing a command that would aggravate the damage.

Figure 7 shows what has been described as one of the most complex test articles ever built to perform Live Fire Testing. The 46th Test Wing designed and built a full-scale replica of the F–35 aircraft for the purposes of dry bay fire extinguishing system tests. The 46th Test Wing received design data from LM during the PDR phase of the program and converted this data into a simplified, yet very representative test article. The test article is heavily instrumented with thermocouples, heat flux gauges, pressure transducers and strain gauges along with regular speed and high-speed video cameras. NGC and Kidde Aerospace are providing the new, active agent technology for fire suppression. Although it is too early to report findings, testing is continuing to refine the design and installation of the dry bay fire detection and suppression system. The F–35 "iron bird" will be used extensively over the next several years to study various vulnerability issues on the aircraft and will be available in the out years in the event a need arises to investigate any new technologies or vulnerabilities that may arise.

As mentioned earlier, new technologies for testing are being implemented for the F–35 program to insure the proper data is being collected. These include the use of high-speed digital video and tracking software as well as extensive instrumentation. Both the 46th Test Wing and NAWC China Lake have incorporated high-speed digital video into their testing. This video imagery allows the use of specialized software that can track the mass and velocity of individual particles, like spall. A unique use of this capability is doing airflow

Figure 4. Hydrodynamic Ram Mitigation Test

Figure 5. Lift Fan Drive Shaft Ballistic Tolerance Test

Figure 6. Three Bearing Swivel Duct Ballistic Tolerance Test

measurements using helium bubbles. By tracking the movement of each bubble, its velocity, and direction can be measured as well as the motion displayed and recorded on video. The use of timed strobe lights is benefiting the high-speed video and providing superb lighting to prevent dark images. Work is beginning on development of high-speed video capability, internal to the test articles. Most of the testing completed to date has been extensively instrumented to provide data not only for design, but also to refine the M&S activities accompanying all F–35 test programs.

A major lesson learned so far in the F–35 Live Fire Test program is the lesson of testing early. As most of us have learned over the years, the sooner test data can be incorporated into the design the more likely the design trade will be incorporated into the aircraft. However, when the aircraft design is still maturing, testing early poses significant challenges. By the time the test plan is drafted and the test article constructed, we have experienced several instances where the aircraft design changed and modifications to either the article or analysis were made. Testing early is still the preferred way to proceed, however caution must be used in this approach.

In conclusion, the F–35 Live Fire program is on its way to achieving its goal for providing maximum, high quality data. The Live Fire program will continue to develop data that will be used to establish higher confidence in the vulnerability analysis as well as provide data for Pre-Planned Product Improvements (P3I). With the first year of testing behind us, we continue to look ahead to the Full-Up System Level tests that are just over the horizon. ∎

Mr. Rhoads received his B.S. in Aerospace Engineering at the Pennsylvania State University in 1990. He has been performing vulnerability assessments on aircraft since 1990 and joined the Lockheed Martin team in 1997. Currently he is the lead of the F–35 Live Fire Test program responsible for writing and leading several of the test programs as well as conducting analysis and trade studies. He served on the AIAA Survivability Technical Committee from 1996-2002. He may be reached at 817/777.9498.

Figure 7. Dry Bay Fire Extinguishing Iron Bird Test Article

Joint Live Fire/Aircraft Systems Program (JLF–Air)

■ by Mr. Jeff Wuich

The Joint Live Fire (JLF) Program was initiated by the Office of the Secretary of Defense (OSD) in March of 1984 to establish a formal process to test and evaluate fielded U.S. systems against realistic threats. The program continues today under the auspices of the Deputy Director, Operational Test and Evaluation/ Live Fire Testing (DDOT&E/LFT). The JLF Program was chartered to assess the vulnerability of fielded U.S. armored vehicles and combat aircraft to threats likely to be encountered in combat and to evaluate the lethality of fielded U.S. munitions against realistic targets. The Joint Aircraft Survivability Program Office (JASPO) and the Joint Technical Coordinating Group for Munitions Effectiveness (JTCG/ME) are the executive agents for the JLF Program, aircraft and ground/mobile systems, respectively, while the Services execute and support the tests under joint leadership. The JLF Program consists of three groups: Aircraft Systems (JLF–Air), Armor/Anti-Armor (JLF/A/AA), and Sea Systems (JLF/SS). JLF–Air focuses on the vulnerability of U.S. fixed-wing and rotary aircraft to realistic threats and on the lethality of fielded U.S. weapons/munitions against foreign aircraft. This article features JLF–Air projects receiving FY04 funding.

The DDOT&E/LFT intends to more closely integrate the JLF Program into other focus areas within DOT&E, such as integrated survivability assessments and increased understanding of vulnerabilities of legacy systems; and to leverage the program with other DOT&E investment programs (Threat Systems Office, JASPO, JTCG/ME, Center for Countermeasures, and Live Fire Testing and Training Initiative). To that end, the DDOT&E/LFT has approved JLF–Air projects for FY04 that will provide empirical data on the vulnerabilities of some of our currently fielded aircraft platforms. These data will be made available to the test and evaluation community at large and to the system program managers. The FY04 JLF–Air Program consists of vulnerability tests and assessments on the following fielded rotorcraft and fixed-wing aircraft: the AH–1, CH–47D, CH–53E, H–60 and the Predator unmanned aerial vehicle (UAV). The vulnerability of a large turbofan engine to the MANPADS threat will also be initiated in FY04.

AH–1 Testing

As we have seen in recent armed conflicts, our front-line helicopter systems are susceptible and vulnerable to attack from readily available threats. One of the threats of primary interest to the vulnerability test and evaluation community is the rocket propelled grenade (RPG). The JLF–Air FY04 Program will investigate the vulnerability of the AH–1 Cobra front-line attack helicopter to this threat. The goal of this effort is to identify potential survivability enhancements for this and other helicopter platforms.

In FY04, JLF–Air will enter the second year of a tri-service (Army, Navy, and Air Force), multi-year investigation of the vulnerability of helicopters (represented by the AH–1) to RPGs. This effort represents the first empirical vulnerability investigation of helicopters to this threat. It will also provide information to aid combat mission planning, aid battle damage assessment and repair training, provide vulnerability reduction recommendations and increase aircraft/aircrew survival and effectiveness in combat. Army test planning was completed in FY03 at the facilities of the Survivability/Lethality Analysis Directorate (SLAD) of the Army Research Laboratory (ARL) —Aberdeen Proving Ground, Maryland. Testing is scheduled to begin in 1st quarter FY04. The Army tests, employing plate arrays and actual helicopter structures as targets, will examine "first-contact" impact parameters including fuze sensitivity, structure penetration, and (combined) damage mechanisms. Navy tests are scheduled to begin in FY04 at the facilities of the Weapons Survivability Laboratory of the Naval Air Warfare Center Weapons Division (NAWCWD)—China Lake, California. These tests will investigate the self-destruct "air-burst" RPG against an arena of plates followed by tests against an AH–1S to gather data and compare damage mechanisms (e.g., damage created by "air-burst" encounter compared to damage created by "first-contact" encounter). The RPG project will culminate in FY04 at the 46th Test Wing facilities—Eglin AFB, Florida with tests events against a full-up, operational, instrumented AH–1 helicopter. Quick-look reports will be prepared upon completion of testing by each Service. A single, final report will be prepared in FY05 that will include combined analysis of RPG lethality and AH–1 vulnerability to "first-contact" and "air-burst" fuzing. The ARL project engineer for this effort is Mr. Robert Kunkel, the NAWCWD project engineer is Mr. Hau Nguyen and the 46 OG/OGM/ OL–AC project engineer is Mr. Pat O'Connell.

CH–47 Testing

In FY04, ARL will complete a JLF–Air effort in partnership with the Cargo Helicopter Program Manager (PM), DoD, and commercial armor developers to design, manufacture, and qualify a shield that will reduce the probability of fuel fires resulting from small caliber projectile impacts on the engine fuel feed

shutoff valve located in the CH–47D Chinook helicopter. Testing will be conducted at the ARL/SLAD facilities—Aberdeen Proving Ground, Maryland. This effort will provide information to aid combat mission planning, increase aircraft/aircrew survival and effectiveness in combat, aid battle damage assessment and repair training and provide recommendations for more survivable helicopter fuel feed shutoff valves. The overall results are applicable to two fielded Army H–47 models (i.e., D and E; the latter is a special operations aircraft that has seen extensive combat use in Afghanistan and Iraq) and the future production F model. ARL will deliver a proven shielding design to protect rotorcraft fuel components, a detailed test plan, a pre-shot prediction report, and a detailed test report. The ARL project engineer for this effort is Mr. Steve Polyak.

CH–53 Testing

In FY04, JLF–Air will enter the second year of a multi-year investigation into the vulnerability of the CH–53E platform. Threat munitions to be used during this effort include small arms/automatic weapons (SA/AW 12.7 mm API and 14.5mm API) and anti-aircraft artillery (AAA – 23mm API & 23mm HEI). Ballistic testing will be conducted at the NAWCWD facilities – China Lake, California. This effort will provide information to aid combat mission planning, increase aircraft/aircrew survival and effectiveness in combat, aid battle damage assessment and repair repair training and provide vulnerability reduction recommendations. The first year of this effort (FY03) concentrated on test planning and asset acquisition. In FY04, ballistic tests will be conducted against CH–53E rotor and drive subsystems (main and tail rotor blades, pylon fold, tail drive shaft) under representative dynamic loads. These tests will be used to gather damage data and perform post-damage operating endurance testing on dynamic components to evaluate the reduction or loss of dynamic flight load capability. In FY05, ballistic tests will be conducted against CH–53E fuel systems and dry bays. These tests will be used to assess the vulnerability of the CH–53E to ballistic threat-induced

structural removal/damage as a result of ullage explosion and/or dry bay fire. A final report containing results from the entire project will be prepared in FY05. Information collected from this effort will be used to verify/validate the 1979 CH–53E vulnerability assessment. The Navy project engineers for this effort are Mr. John Gallagher (NAWCAD) and Mr. Joe Manchor (NAWCWD).

H–60 Testing

In FY04, three H–60 efforts are funded under JLF–Air. Dry bay foam vulnerability reduction alternatives, improved durability gearbox (IDGB) run-dry ballistic vulnerability tests and H–60 engine nacelle fire extinguishing system effectiveness against ballistic threats.

Recent ballistic testing with the UH/MH–60 main fuel subsystems identified issues with the reticulated foam installed in the dry bay areas surrounding the main fuel cells. ARL will investigate replacement materials for the current UH/MH–60 fuel cell dry bay foam under the JLF–Air Program in FY04 and FY05. Test planning will occur in FY04 and the ballistic test series will be conducted in FY05 at ARL/SLAD's Experimental Facility 6 (EF6) located at Aberdeen Proving Ground, Maryland. This effort will provide information to aid combat mission planning, increase aircraft/aircrew survival and effectiveness in combat, aid battle damage assessment and repair training, and provide vulnerability reduction recommendations. The results of this project will be applicable to all tri-service H–60 fleet of aircraft and the future production of the Army's UH–60M model. ARL will deliver a detailed test plan, a pre-shot prediction report, and a detailed test report. The ARL project engineer for this effort is Mr. Fred Marsh.

In FY04, ARL will investigate the "run-dry" tolerance of the improved durability gearbox (transmission), currently fielded in several versions of the H–60 helicopter. Test planning will occur in FY04 and the ballistic test series will be conducted in FY05 at ARL/SLAD's EF6 located at Aberdeen Proving Ground, Maryland. The results of this project

will be applicable to all tri-service H–60 fleet of aircraft and the future production the Army's UH–60M model. ARL will deliver a detailed test plan, a pre-shot prediction report, and a detailed test report. The ARL project engineer for this effort is Mr. Fred Marsh.

A tri-service Army, Navy, and Air Force effort was initiated in FY02 to conduct parametric controlled damage and ballistic tests to evaluate the influence of varied damage levels to the effectiveness of the current H–60 aircraft engine nacelle fire suppression system with current and alternative fire suppression agents. The main issues are:

1. Halon 1301 engine nacelle fire suppression systems are not designed to account for the changing conditions that are incurred as a result of combat damage. Ballistic damage may alter the conditions within an engine nacelle so as to hinder the protection afforded by these systems, and;

2. Halon 1301 environmental issues have resulted in some aircraft programs transitioning to alternative fire suppression agents and systems. The effectiveness and limitations of these new systems in suppressing ballistically induced fires is unknown.

In FY02, the Aerospace Survivability and Safety Flight (46 OG/OGM/OL–AC–WPAFB) conducted parametric controlled-damage testing of a simulated H–60 Halon 1301 engine nacelle suppression system. The Aircraft Engine Nacelle (AEN) simulator was modified to representative H–60 dimensions and environmental conditions. These tests are being used to determine damage effects and suppression agent design concentrations within the nacelle, determine possible vulnerabilities as input for follow-on NAWCAD engine nacelle tests and to provide leveraging opportunities for Halon alternative agent tests. In FY03, NAWCAD conducted controlled-damage and ballistic tests on the H–60 Halon 1301 engine nacelle suppression system. An H–60 engine

Figure 1. H-60 Engine Nacelle Fire Suppression System Test Setup

nacelle with non-running engine and component clutter under representative environmental (airflow) conditions was used. These data provide input for follow-on (FY04) NAWCWD running engine/systems tests and provide leveraging opportunities for Halon alternative agent tests. In FY04, NAWCWD will conduct ballistic demonstration/ data validation tests on an H–60 engine nacelle suppression system. An engine nacelle with operating engine and related nacelle systems under representative environmental (airflow) conditions will be used. These tests will help to identify locations vulnerable to ballistically induced fires and will also provide leveraging opportunities for Halon alternative agent tests. The Air Force project engineer for this effort is Mr. Pat O'Connell (46 OG/OGM/OL–AC), the Army project engineer is Mr. Fred Marsh (ARL) and the Navy project engineers are Mr. Joe Dolinar (NAWCAD) and Mr. Joe Manchor (NAWCWD).

Predator Testing

Until now, unmanned aerial vehicles (UAV) have been designed strictly for mission effectiveness—vulnerability reduction was not a consideration, as most UAVs were considered expendable. However, UAVs continue to grow in numbers and cost, and as their mission value grows, they will no longer be considered expendable. There is a growing interest in implementing enhancements in UAV designs to provide the mission commander with a more survivable aircraft. In FY04, the JLF–Air Program will conduct system vulnerability testing of a Predator fuselage and subsystems (fuel, propulsion, and control) mock-up before and after select vulnerability reduction features are in place. In keeping with the DDOT&E/LFT's desire to more closely integrate the JLF program to other DOT&E investment programs, shotlines for this effort will be based on the COVART analysis previously completed under the JASPO Predator Vulnerability Analysis (FY03). This analysis identified vulnerable areas in the current Predator design that can be addressed in future builds. This project directly supports the UAV Program Office (ASC/RAB – WPAFB) in identifying vulnerability reduction improvements that can be made to present, or future blocks of the aircraft. These lessons learned can be applied to other UAVs/UCAVs as well. The Navy project engineer is Mr. Jim Young (NAVAIR) and the Air Force project engineer is Mr. Pat O'Connell (46 OG/OGM/OL–AC).

Large Turbofan Engine Testing

In FY04, JLF–Air will initiate a multi-year effort to investigate the vulnerability of the CF6 large turbofan engine to MANPADS. The following long-standing issues will be addressed: 1) What is the inherent vulnerability of an operational CF6 engine hit by a MANPADS? 2) How does the hit-point and damage-state compare to pretest predictions? 3) How does the damage affect engine operation and thrust? 4) How will the thrust alteration affect safety-of-flight? and 5) If damage produces a kill, what is the kill mechanism? Test planning will occur in FY04. In FY05, MANPADS tests will be conducted on non-flight worthy CF6 assets in order to conduct a quick-look assessment of engine vulnerability, which will be correlated with LS Dyna 3D damage predictions (a JASPO FY04 new-start). Damage affects on engine thrust and safety-of-flight (GE & NASA roles) will be assessed. In FY06, a MANPADS test will be conducted on a flight worthy, wing-mounted CF6 engine to obtain full-up assessment of engine vulnerability. Test results will be compared to pretest predictions involving hit-point and damage state. Engine thrust and safety-of-flight issues resulting from the damage will be assessed. A detailed test plan, pretest predictions and a JLF–Air final report describing large-engine vulnerability to MANPADS and potential effects of safety-of-flight issues will be delivered. Test results from this effort will support large aircraft (i.e., C–17, KC–767 and E–10A) operational risk assessments and vulnerability analyses leading to improved warfighter protection. Results of large engine characteristics to MANPADS impact and detonation identified during this effort will be used to feed future large engine design and evaluation requirements. Mr. Greg Czarnecki and Mr. Nathan Cook (46 OG/OGM/OL–AC) are the Air Force project engineers for this effort. ■

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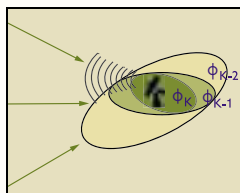
New Ways to Locate a Threat

■ Dr. Stephen W. Schneider, Dr. Robert Penno, Dr. Krishna M. Pasala, and Dr. Leo Kempel

Paramount to the survivability of airborne systems is the ability to locate lethal threats quickly and accurately in a dense signal environment—separating them from all of the benign sources present in the spectrum. These signals cover a wide range of frequencies from a variety of locations depending on the role or tactical mission of the platform. Hence, emitter location is a challenging problem.

An emitter location system determines the location of a source of electromagnetic energy in a global reference system. One way to accomplish this goal is to periodically estimate the bearing of the emitter over a known flight path. Hence, the accuracy with which the emitter location can be estimated depends on the quality of the bearing or "angle-of-arrival" (AOA) estimates that are generated by the direction finding (DF) system. Different direction finding systems are capable of different accuracy; however, the performance of all these systems is degraded by noise. A typical measure of performance is the Signal-to-Noise Ratio (SNR), which is the strength of the signal of interest (in this case, a threat emission) relative to the background noise (caused by other emitters, both friendly and threat, and natural sources). The higher the SNR of the system is, the better its accuracy.

Although airborne platforms are used for a variety of missions, their operational environment may be broadly separated into two categories—stand-off platforms and penetrating platforms. These two scenarios are shown in Figure 1. In the stand-off scenario, the platform is positioned well away from the theater of operation and, as such, is less vulnerable than the penetrating platform. Its function is to monitor and evaluate the entire theater of opera-
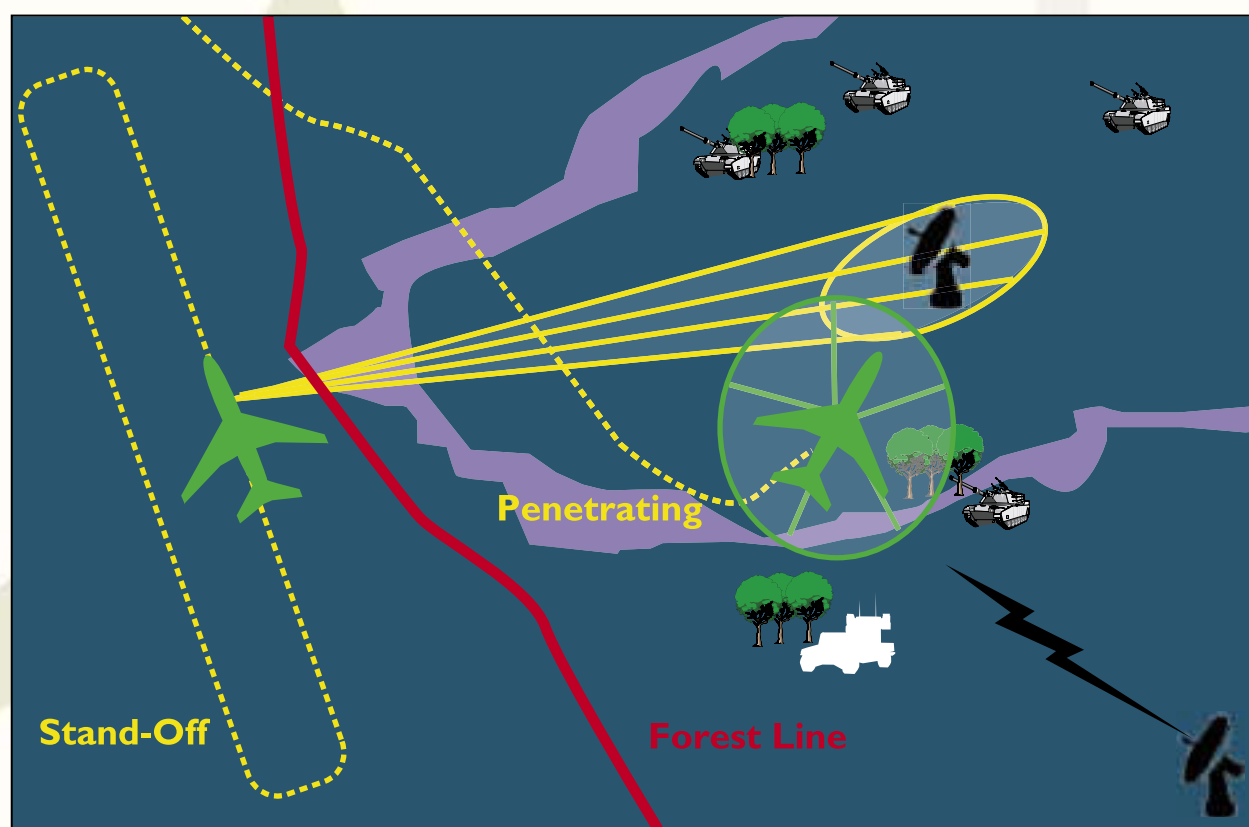

Figure 1: Typical Threat Scenario

tions and share information with all the assets in the region. Since the platform is remote from its area of coverage, more sensitive, higher gain systems are required. Since the field-of-view (FOV) is limited to only a single quadrant of the aircraft, higher gain antennas may be utilized.

Penetrating platforms operate in a high threat environment and their vulnerability is a serious concern. These platforms are capable of delivering munitions accurately and efficiently to neutralize a threat and they carry an array of systems to attain this goal. In addition, it is

desirable that these systems be capable of either avoiding or disabling the threat. Such additional capabilities provide greater situational awareness—a much coveted tactical advantage. Since these platforms may approach the threat from any direction, omni-directional angular coverage is required. Due to the proximity of the threat systems, low gain, less sensitive systems may be employed. However, the placement of these antennas on the platform is a significant issue; these antennas must compete with a whole host of other antennas supporting a variety of functions. The problem is especially

severe if different antennas must be used to cover a wide frequency band. Indeed, it is best to use a single aperture that can accommodate all the frequency bands-of-interest. The Air Force Research Laboratory (WPAFB), with support from JASPO has been engaged in novel approaches to this vexing problem.

Existing Techniques for Locating a Threat

The first step in determining the nature of a threat is to determine its AOA. A variety of methods have been used to provide threat AOA information, including interferometry, classic array beam-forming and parameter estimation techniques applied to linear arrays of identical antennas. All of these methods require multiple antenna elements and usually are adversely affected by wide variations of frequency. Typical of these approaches is the linear phase interferometer. Three antennas are located along two perpendicular baselines, forming an L–shaped configuration. The longer (electrically) the baselines are, the higher the resolution, or accuracy, of the AOA estimate. Phase differences at the three antennas are computed based on the incident signal, producing estimates of the AOA relative to the two baselines. These are easily converted to elevation and azimuth estimates. Unfortunately, any baseline longer than one-half wavelength produces multiple AOA estimates. These ambiguous solutions, called "grating lobes" in antenna theory, must be discarded in favor of the correct solution. To accomplish this, two other antennas are added, one each along each of the two baselines, and situated within one-half wavelength of the antenna common to both baselines. The unique AOA estimate produced by this short baseline pair, while not very precise, is accurate enough to select the correct solution from the possibilities available from the long baseline pair. This five-element system, the Linear Phase Interferometer (LPI), works well as long as the long baseline is long enough to provide the required accuracy, and the short baseline is electrically short enough to remain unambiguous.
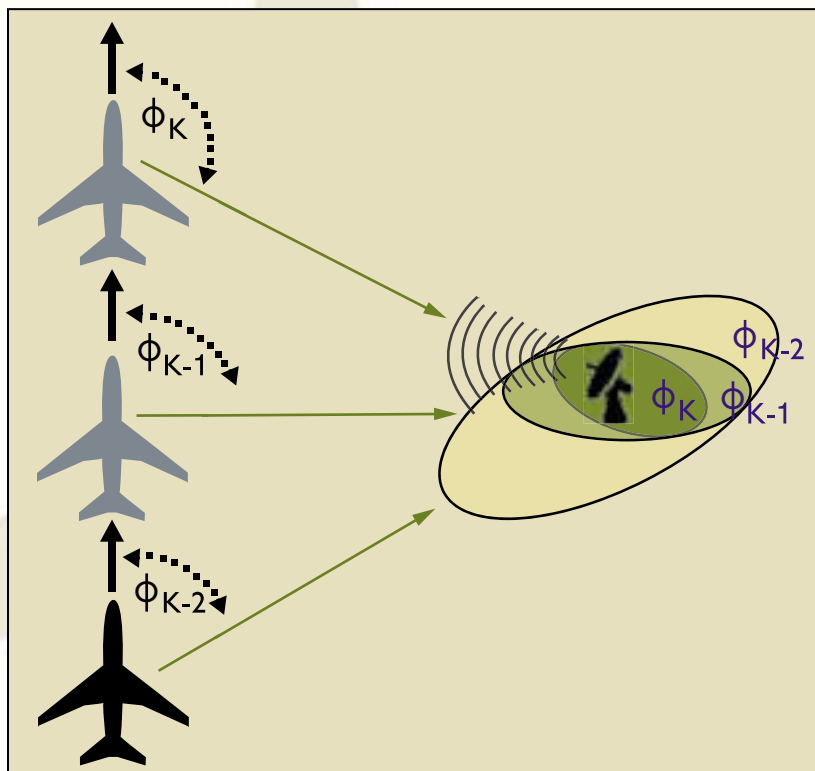

Figure 2: Conventional Antenna Farm

Figure 3: Multiple AOA Estimates to Locate Signals

Unfortunately, as the frequency increases, a spacing of one meter is one half wavelength at 150 MHz but becomes a spacing of two wavelengths at 600 MHz. At this higher frequency, the AOA estimate is itself ambiguous! Lowering the frequency to, say 75 MHz, doesn't help, since both baselines are electrically half as long, dramatically lowering the resolution of the system. Thus, to determine AOA over a wide band of frequencies, several LPI systems are required. Figure 2 shows a generic collection of systems, an antenna "farm", used to determine AOA over a wide band of frequencies.

Depending upon the scenario, coverage as well becomes an issue. Several "farms" may be needed on an aircraft to assure coverage on either side, downward, forward, and even rearward. Practical considerations such as maintainability, reliability, and application versatility in conjunction with cost, size and weight make it highly desirable to minimize the number of apertures on the platform that are required to determine AOA.

AOA alone does not insure the survivability of the platform. Indeed, accurate threat AOA information must be integrated to produce highly accurate estimates of the actual location of the threat. For the sake of discussion, assume a level, straight flight path of the platform of known speed and location, such as that shown in Figure 3. At known intervals, AOA estimates of the target are made. Using straightforward signal processing techniques, such as a Least Mean Square estimator, or more sophisticated techniques, such as Kalman filtering, successive AOA estimates are used to estimate the actual coordinates of the ground based threat. These coordinate estimates take the form of "error ellipses", and describe a region on the surface that, within a specified probability (e.g., 95 percent), the threat lies. An alternative representation, the CEP (Circular Error Probable), produces a circle whose area defines, with a 50 percent probability, the location of the threat. Moreover, AOA estimates are made, interpreted by the location estimator until an estimate

of the threat's location of a sufficient accuracy is achieved. Time is of the essence, and improved accuracy from each AOA estimate along the flight path is necessary for the platform to rapidly identify threat location, and survive.

New Approaches to Determine Threat AOA: Multi-Mode Antennas Using Comparison Techniques

Multi-mode antennas have been around for a long time and are fairly well understood. They represent a class of apertures, which in essence can be described as multiple co-located antennas designed to provide complementary functions. When used in conjunction with a piece of hardware known as a "modeformer", the terminal outputs are trans-

formed into modeformer outputs which produce "modal patterns" that are unique from each other as shown in Figure 4. By comparing the magnitude of these modal outputs, an estimate of elevation (with respect to antenna boresight) is obtained, while comparison of the phase of these modeformer outputs provides an estimate of azimuth. The modeformer concept has long been used with linear or planar arrays of single-mode antennas; a typical example of such a modeformer is the Butler matrix or the Rottman lens. Here, the modeformer is being applied to a single-aperture antenna.

The multi-arm spiral, shown in Figure 4, is just such a multi-mode antenna, but has the additional feature of being frequency-independent
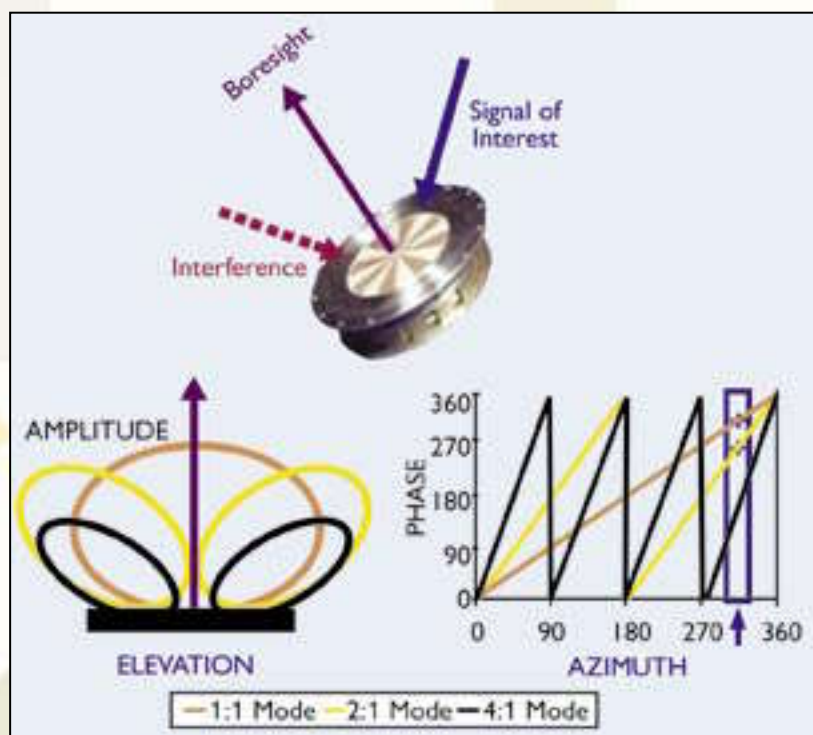

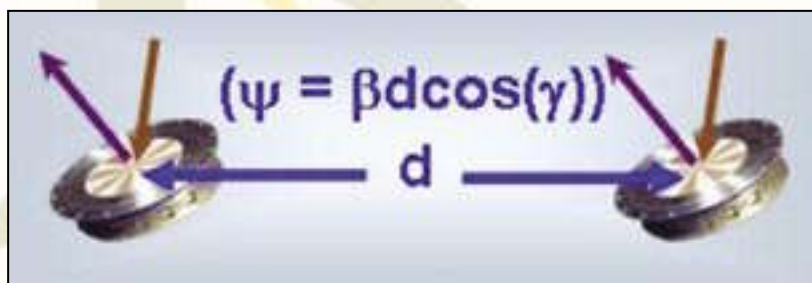Figure 4: A Multi-Arm Spiral and its Modal Field Patterns

Figure 5: Single Baseline of a Hybrid Multi-Mode

over a wide band of frequencies. In these antenna types, the electromagnetic (EM) characteristics are determined by angular relationships, not lengths or widths. In fact, the lowest frequency of operation of the spiral antenna shown in Figure 4 is dictated by the outer diameter of the antenna, or rather the aperture it requires in the aircraft's surface.

This so-called "comparison approach," used in conjunction with the modeformer, has long been used to provide AOA estimates. The four-arm spiral, in conjunction with a modeformer, provides accuracy comparable to that of two single-mode antennas separated by one-half wavelength, also referred to as a half-wave interferometer. The salient aspect of using four-arm spirals instead of half–wave interferometers, however, is that the accuracy of the estimates obtained by the four-arm spiral remains constant over the entire band of frequencies for which the spiral is designed. The estimates obtained from the half-wave interferometer are best when spacing is exactly half-wavelength, and degrade as frequency decreases. Thus, a single four-arm spiral may suitably replace several half-wave interferometers to satisfy wide-band requirements.

Multi-Mode Antennas Using Parameter Estimation Techniques

Consideration of the cost, size and weight of the modeformer required to apply the comparison approach to AOA estimation using the multi-arm spiral led to the investigation of alternative, signal processing based techniques, such as parameter estimation. Examples of such techniques are the Maximum Likelihood Method (MLM) and the MUSIC (MUltiple SIgnal Classification) schemes. To use signal processing techniques, the outputs of the antenna terminals are fed directly into a multi-channel receiver, as opposed to the more simply-constructed receiver used in the comparison approach. Signal processing techniques such as MLM or MUSIC have been successfully applied to linear arrays of single-mode antennas.

The AOA estimates obtained by using MLM or MUSIC were superior to those using the modeformer, but without the modeformer hardware. Another issue little addressed by the comparison approach was spatial coverage. Looking at the modal patterns of Figure 4, it is easily seen that threats from near boresight or near grazing are not as effectively handled by the multi-arm spiral since most of the modes don't have coverage in those directions, i.e. those modes don't receive a significant amount of signal at those AOAs. Using MLM or MUSIC provided much better coverage for threats from these regions, a significant improvement in coverage over the comparison approach. Some of the concerns arising in the use of MLM or MUSIC included sensitivity to channel mismatches, or multipath resulting from platform scattering. However, the use of calibration techniques, or a look-up table approach, provides an effective means of dealing with these errors. While signal processing techniques tend to require more computational power to obtain AOA estimates in real time, algorithm development can offset this demand.

Another interesting feature that results from the use of signal processing techniques is the ability to deal with unintended interference. The AOA of the threat may often be sought while in the presence of other signals that interfere with this measurement. Both the multi-mode antennas (using the comparison method) and the LPI do not perform very well in the presence of such interference. However, it is possible to modify the parameter estimation techniques such that AOA estimates may be obtained even in the presence of interference. While this process results in a slight degradation of the system sensitivity, AOA estimates can be produced even in the presence of high noise and high interference strengths. It is noteworthy that a well-balanced (i.e. channels are phase matched) multi-channel receiver is needed to implement these modern signal processing algorithms. However, modern developments in electronics are leading to reductions in cost and size of these receivers

making it increasingly practical to implement these algorithms.

Hybrid Multi-mode: "Two Are Better Than One"

The multi-arm spiral provides angle estimates over a wide band of frequencies. However, the accuracy of these estimates is not comparable to the accuracy of the estimates provided by the LPI. The accuracy of the LPI comes from the long baseline which is typically many wavelengths long. The accuracy of the multi-arm spiral is on the order of the accuracy of a half-wavelength interferometer. It is natural to seek a hybrid solution that can combine the frequency invariance of the multi-arm spiral with the accuracy of the LPI. Indeed, such a hybrid interferometer is possible and consists of two arms situated on two orthogonal axes. Each arm consists of a long baseline interferometer of two multi-arm spirals as shown in Figure 5. The accurate but ambiguous estimates of the long baseline interferometer are resolved using the relatively coarse but unambiguous estimates provided by the multi-arm spiral. Such a hybrid system yields accuracies comparable to the LPI and, in addition, works well over a wide band of frequencies. There is an upper limit on the highest frequency, or equivalently the longest baseline, allowed for a given signal-to-noise ratio (SNR) at which the system can operate well. This limitation occurs when the "spread" in the angle estimates obtained from the multi-arm spiral exceeds the separation between the "spreads" of two possible adjacent solutions. It may be noted that the hybrid interferometer consists of three multi-arm spirals instead of the five antenna elements, as in a conventional interferometer. This Hybrid interferometer yields accuracies comparable to the LPI and in addition works well over a very large range of frequencies. However, in both systems the SNR is required to be higher than a threshold value that depends on the baseline separation. It is possible to apply the MUSIC algorithm directly to the Hybrid configuration of three multi-arm spirals, arranged along perpendicular axes. Here, AOA determination does not require explicit resolution of ambiguous

AOA solutions. In addition, while it does require more computation, it yields better estimates of AOA than the Hybrid interferometer.

Where do we go from here?

Work continues in the application of this approach to better determine threat AOA. Currently, MUSIC is being applied to a single, multi-mode antenna to determine AOA's of multiple threats, all in the presence of incoherent interference. It is straightforward to extend this to multiple, multi-mode antennas, configured as a Hybrid interferometer, to perform this task with the higher accuracy obtained with long baseline separations. Challenges to the practical implementation of this technology include the expense of multi-channel receivers, as well as the availability of the high speed, computational power required to perform these tasks in a timely fashion. Over time, however, the cost of multi-channel receivers continues to drop as development continues. Likewise, algorithm development will likely mitigate the requirement for computational power and speed. This makes achievable the goal of assisting the warfighter in prioritizing threats in a dense signal environment, thus ensuring survivability and mission success! ■

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Passive Protection of Aircraft Against Fires and Flammable Fluid Deflagrations

■ by Mr. Guy L. Gettle, Mr. Vincent H. Homer, Jr., and Mr. Donald R. Kennedy

Fixed-wing aircraft, helicopters, and unmanned aerial vehicles (UAVs) all proved essential to the Allied victory in Operation Iraqi Freedom. Aerial reconnaissance identified targets that could be quickly attacked and spotted routes that enabled mobile forces and critical supply convoys to penetrate with minimum delay. Attack helicopters often immobilized Iraqi units and disrupted their logistical support. Helicopter-borne troops seized bridges and forward airstrips and ambushed Iraqi maneuver forces. Other helicopters, and even cargo aircraft, supplied advanced units otherwise in potential peril, as well as helped to open a second front.

We have witnessed two large-scale operations and several smaller ones by U.S. forces during the last two years in regions furthest from American shores. Each of these has been conducted with vulnerable lines of communication and with limited local air assets until bases could be built. Future conflict zones appear likely to be similarly remote places, where our forces will operate on a logistical shoestring.

Operation Iraqi Freedom was yet another reminder that American air assets need to be fully mission-capable in the low-altitude battlespace. We must also acknowledge another important fact: despite the brilliant performance and employment of Allied air assets, many of these were hit. All types took losses. The message was clear: future low-altitude battlespace operations will be much more dangerous. Iraqi ground forces inflicted damage on UAVs and all types of aircraft earlier this year despite our outstanding intelligence-gathering, numerous sensor plat-forms monitoring every part of that country, and near real-time responses available to requests for air and missile strikes on anti-air positions.

Had anti-stealth weapons been present or any degree of anti-stealth integration with either gun or missile systems been achieved, Saddam supporters would have inflicted much greater losses this spring. We cannot realistically expect that anti-stealth sensor systems and weapons will be kept out of the hands of potential adversaries forever. By the time that F–35 aircraft are deployed forward in appreciable numbers, these aircraft will face much more dangerous anti-air threats, as will helicopters, airlifters, and UAVs that come into range.

Increasing Survivability in the Low Altitude Battlespace

Aircraft crash when they either lose control or propulsion. Control-related crashes result from incapacitation or confusion of the pilot, failure of control systems, or loss of control surfaces. Propulsion failure may arise from control incapacitation, mechanical damage, or fuel starvation.

Neither landing mishaps, pilot confusion, nor midair collisions can be prevented by aircraft hardening. Nor can hardening prevent electronic component failures or mechanical malfunction of engines and fuel pumps, unless these are brought about by fires and explosions. There are plenty of other hazards that punch holes, explode, and generate on-board fires, however. If we prevent these latter threats from causing lethal control and propulsion problems, then we have dramatically improved aircraft survivability.

Virtually all current-inventory anti-air weapons and those to be fielded in the near-term punch holes. Hole-punching threats (projectiles, laser pulses, fragments) may cause flammable liquid leaks, engine damage, electrical shorts, fireballs, or fuel mist explosions. Either we can try to prevent holes from being punched, or we can try to ensure that the aircraft remains flyable despite behind-the-punched-hole damage.

Since aircraft maneuvering in the low-altitude battlespace fly in all sorts of attitudes, there are many potentially lethal shot-lines. Armoring to prevent hole-punching is simply not a cost-effective, weight-efficient route. Let us pursue the alternative: prevent internal damage from causing loss of control and propulsion.

Internal explosions (deflagrations, technically) may cause massive disruption of electrical and fuel systems, and lethal damage to the aircraft structure (ribs, spars, skin panels, etc.). If the hole-punching threats fail to cause an instantaneous explosion, penetrator-caused fires remain a lethal threat. However, if we suppress explosions and protect against sustained fires, then we remove much of the ability of hostile missiles, gunfire, and even laser bursts to inflict lethal damage to aircraft and UAVs. This is technically achievable now.

Our Mission

Recognizing the substantial costs inherent to a comprehensive product development program for survivability systems and components as well as the need to optimize materials selection and design details as rapidly as possible, a unique, modular test facility that allows simulation of aircraft fuselage fuel tanks and con-

tiguous dry bays has been designed. This facility can approximate combat and accident damage to aircraft over a wide range of scenarios and with simulated anti-aircraft munitions.

A minimum-weight, minimum-space applications of materials definition is being sought that will enable aircraft (both fixed- and rotary-wing) and unmanned aerial vehicles (UAVs) to survive sustained high-intensity fires and deflagrations (fireballs and fuel mist explosions). Our mission is to provide solutions that are independent of mission profile or source of ignitions.

Screening tests to be conducted in the SPT facility will determine which materials and components offer the greatest fire protection potential, and the optimum means of using them (by themselves and in the best combinations). Subsequent trials will evaluate a range of combat damage scenarios, including different shot lines, simulated fragment and high-explosive incendiary (HEI) projectiles, and a range of fuel tank ullage volumes.

What will be evaluated? Lightweight assemblies and materials have been developed during the last six years that can suppress flammable fluid deflagrations (fireballs and non-detonating explosions), mitigate fireball incidents, and resist intense fires. Thin honeycomb arrays with an attenuating medium trapped within screen "skins" and panel arrays of narrow-diameter tubes offer the potential for more compact and effective alternatives to reticulated foams for suppressing ullage deflagrations. Unlike reticulated foam, they are effective in dry bay environments.

New fire barrier products include fiber-reinforced epoxy sheets and laminates with "bubble wrap" interior layers that intumesce under fire exposure and can continue intumescing continuously for hours, along with fire resistant insulations. Honeycomb and frame components can be made from these intumescing epoxy resins. Honeycomb and lattice-core panels can be made with combinations of these materials,

protecting the weak char produced by intumescing from fluid and gas impingement and thereby providing substantially increased prolonged flame tolerance. These new materials, and means of using them, offer unprecedented options to aircraft and UAV designers.

The enhanced-capability intumescing sheets, insulations, and coatings can substitute for thermal and acoustical insulations currently used and may be bonded to composite armors to produce fire barrier armor plates. Honeycomb-core panels comprised of the intumescing materials can substitute for existing panels, and can accommodate conduit and piping penetrations in the same way as conventional panel assemblies. These intumescing resin components are bonded, fastened, drilled, repaired, and cut no differently than those that they would replace.

Being entirely passive, the subject protective components function regardless of aircraft orientation, speed, and availability of onboard power. Their performance is not limited by scenario. They also offer multiple uses, but precisely how must be determined in realistic simulations of their service environment.

Specific Fire & Explosion Protection Design Considerations

Solutions must satisfy both the hazard issues and perform in military service environments. To the fire and explosion problems, we must add requirements for:

- Vibration and impact resistance

- Compatibility with aircraft materials

- Acceptance of cleaning, lubricants, solvents

- Access to maintenance and inspection points

- Thermal expansion compatibility

- Means of attachment or bonding (including re-attachment)

- Acceptable weight and dimensions

- Desired electromagnetic and static electricity characteristics

- Cost and availability

Regarding hazards to aircraft and UAVs, the fire problem is more pervasive, so let us address that first.

Protecting Against Fire

A "universal solution" for aircraft fires has yet to be found. So far, fire-retardant additives have not been able to give resins used for composites and sealants the capability to withstand intense fires for useful time durations. So much additive is typically required that the resins themselves lose the desired mechanical properties. Ablative and refractory materials are invariably heavy and are almost invariably brittle. These materials are prone to mechanical damage, and small flaws generally lead to failure under vibration and incompatible thermal expansion with substrates. Mechanical (active) fire and explosion suppression systems require activation, agent, and hardware. They offer neither insulation, armor nor other alternative use to aircraft operation.

Intumescent materials offer great promise. Theoretically, they can provide fire resistance in a much thinner and lighter layer than alternative materials and circumvent the brittleness problem of many fire barrier products. Most intumescent coatings, however, generally fail to stand up in their "day job" role in military applications—being a coating. Furthermore, the char produced by intumescing is weak, is easily removed by strong gas flow, and often allows flame penetration at sharp edges. Intumescent layers are not great thermal or acoustic insulators, which is a problem for substrate materials that degrade or ignite at lower temperatures, such as wire insulation and many composites.

Two approaches are being pursued: (1) using existing intumescing coatings in configurations that protect them against their present vulnerabilities, and (2) substituting existing

components with materials only now becoming commercially available. Our solution to the problem of weak char—using existing materials—is to put the intumescing coating inside a honeycomb or lattice. The "fireside" surface can be any desired material (depends upon the environment). Once the intumescing reaction begins, char will fill the cells of the honeycomb, thus producing considerable thermal resistance, while isolating the char from erosive gas flow—including any outside air rushing through openings in the aircraft skin.

The internally-intumescing panels can be curved or flat and be used as bulkheads, floors, and integral tank walls. Other protective and insulating layers can be provided in order to provide desired acoustic attenuating and thermal barrier properties. This is a particularly good example of our emphasis on multi-use substitutions for existing components that meet fire and explosion protection criteria.

Three new materials that are of immediate interest to our effort: (1) intumescing epoxy resin sheets (unreinforced and fiber-reinforced); (2) Infrared (IR)-reflective insulating coatings; and (3) clear intumescing coatings. The sheet materials (trade-named Pyro FireblokTM) can be (and have been) laminated to a wide range of materials, whether rigid or flexible—metal foil, polyurethane foam, "bubble wrap", ballistic barrier textiles, and more. The IR-reflective coatings (tradenamed Super ThermTM) are water-based, can be applied by spray, and dissipate more than 99 percent of IR radiation. These can be applied over, or be coated by other intumescing coatings and other surface treatments, including paints without significant loss of insulating properties. The clear intumescing resin (tradenamed PyroflexTM) can be used for creating transparent and translucent panels, including versions of the above-mentioned honeycomb panels where char is protected from outside environments.

The intumescing resin system and the IR-rejection insulation open up some unanticipated opportunities for survivability. Intumescing epoxy films can be laminated to produce fire barrier armor. The resins can be used to coat conduit and armored tubing for wires and fluid lines. The IR-dissipative insulations can conceivably be used to reduce thermal signatures for aircraft skin panels, or alternatively generate "spoof" IR patterns, thus overlapping with vulnerability reduction techniques.

The new intumescing system embedded in the epoxy resin has demonstrated a remarkable expansion capability—well over 100 times the unreacted coating thickness. This offers another means of protecting against dry bay fires: substantially or completely filling the free volume with char, thereby smothering the flames. This also would prevent deflagrations in the dry bay in the event that fuel mist enters a space in which flames are already present, since gaseous combustion products produced from poorly-oxygenated flames would limit the zones within the explosive range.

Explosions

A practical and useful scheme for preventing catastrophic loss due to deflagrations must:

- Prevent fuel vapor ignitions from causing catastrophic loss of containment

- Prevent or suppress fireball formation due to fuel vapor ignitions

- Substitute for existing components to minimize weight and structure impacts to a substantial degree

- At least meet fire barrier, flame spread, smoke & toxicity limitations, and improve upon the minimum values to the maximum possible extent

- Avoid adding a hazard during an explosion or fire

- Avoid increasing maintenance frequency or significant inspection costs

- Avoid compromising safety or operation in cases of failure, damage, misfit, or defect

Fuel deflagrations in tanks and dry bays have been extensively investigated by many researchers in the US and abroad. The actual hazard is a rapidly moving flame front burning in partially- or fully-confined fuel vapor or mist. Our experience in full-scale tests in the 1990s is that panel-type assemblies that encourage flame fronts to penetrate into bead-filled panels readily extinguish these flames upon impingement.

How? These assemblies rapidly extract heat from impinging flame fronts and block radiant pre-heating of unburned species, thereby dropping the flame front environment below the lower flammability limit (LFL). Unlike water mists, mitigating panel baffles quench flame fronts before the induced turbulence can accelerate their propagation. The deflagration extinction processes of narrow-tube arrays, bead-filled honeycomb, and various arrangements of large surface area media in lightly-packed grilles are independent of the source of ignition and virtually unaffected by fuel type.

By placing mitigating panels in a baffle arrangement and in sufficient number, flame front extinguishment can keep internal pressure within airframe manufacturer-specified limits. The low weight of mitigating panels and their supports would keep inertia loads low in the event they would be subjected to hydraulic ram or high kinetic energy penetrator interaction.

Test Rig Design

Having identified and (roughly) specified candidate test materials and means of their use, the most promising materials must be completely characterized and identified. Also the details of their optimum usage, including mounting, location, and thickness must be determined. To accomplish these objectives, a generic test rig that can be used to simulate military aircraft environments was developed (Figure 1). A similar arrangement can be quickly developed for UAVs, with their

different geometry and "train" of compartments, but the initial effort is focused on reproducing fuselage, wing/blended body transition, and wing sections.

With this test rig, scenarios can be simulated ranging from parked aircraft fires to maneuvering attitudes for low-altitude penetration missions. There is no standard test to accomplish all of the goals, so we are setting the initial environment parameters, such as—skin surface temperature ranges (inside and out), volume and dimensions, fluids, chemical exposure (including salt spray, cleaning solvents), fire durations, fuel flow rates, and heat fluxes are being set. High-speed and high-pressure air can be readily injected when necessary.

The test rig design strives to represent the characteristic high thermal conductivity of aircraft metal sheet and structural shapes. There are thin sheets to simulate skins and heavier sections to represent the "heat sink" of spars, stringers, and other shapes. Panels can be readily substituted to place composites and other materials in the intense flaming environment, or to simulate other conditions.

In its initial configuration, the simulated dry bay is 0.72m tall x 0.72m wide x 0.62m long (28.5 in. x 28.5 in. x 24 in.). Volume is $0.33m^3$ (11.5 ft^3). The "aft" bulkhead has protected camera ports. Thermocouple

Figure 1. The test rig with top panel removed, showing placement of test panels. Deflagration-suppressing panels, in later tests, would be placed across the narrow width to prevent explosions. High-performance intumescing panels could be similarly employed in order to fill much of the free volume and thereby smother fires captured during testing.

and pressure transducer mounts will be used, and connected to data loggers. Other types of sensors, such as radiometers, and imagery will be added to document certain phenomena. The "forward" bulkhead serves to protect the fuel reservoir. Fuel line with nozzles appropriate to the scenario being simulated, along with ignition means, pass through this bulkhead.

Test panels are placed vertically on either side (Figure 2), enabling more than one sample to be evaluated simultaneously against the same fire or blast exposure Figure 3 shows panels after simulated ruptured fuel

Figure 2. Test panels after exposure to kerosene flames (with piloted propane ignition source). Venting of smoke was allowed at the 4 open vertical joints. The black char bubbles are due to intumescing (swelling), created by the release of water vapor and carbon dioxide from the resin. Intumescing compounds are in the coating of left-hand panels; in the epoxy resin of the right-hand panels.

Figure 3. Reverse side of upper test panels. Intumescing coating was used as witness material, since reaction temperature (approximately 600° F) falls within aluminum strength reduction range—a condition to avoid! Aluminum temperature remained below the intumescing point for all panels in this trial evaluation of the rig, except for localized hot spots where coatings debonded from metal.

line fire test). Samples can be placed in other locations as well, with sensors documenting local conditions. Deflagration suppression panels and other components will be mounted in different orientations in later tests. Dry bay width can be readily expanded with either aluminum or composite panels. Similarly, the fuel reservoir can be enlarged to conduct longer-duration fire tests.

One or both sides can be replaced with modules that represent specific aircraft or generic ones, simulating the blended fuselage/strake/wing area. Other modules can be quickly organized to simulate weapons

and electronics bays. Future plans include simulating the dry bays between twin engines by externally heating one of the longitudinal walls. This will evaluate improved means of suppressing hot surface re-ignition of fuel-fed fires.

This modular test rig concept will enable realistic simulations of aircraft fire to be arranged almost as quickly as test panels and components can be prepared. Modules and data acquisition subsystems can be shop-assembled, moved, and assembled at the test site in very short order. This will allow us to quickly (and inexpensively) evaluate the effects of material or coating thickness, location, performance as a function of heat flux, and conduct other parametric studies, and thereby rapidly identify desirable improvements and the most promising items for future development. Test results will be reported soon.

Conclusion

As long as gas turbine engines and rockets are used for propulsion, with their associated fuel systems and controls, aircraft and UAVs will be vulnerable to potentially lethal combat damage. The lethality of hostile fire is unlikely to decrease in this decade.

Fixed- and rotary-wing U.S. aircraft inventories are unlikely to increase but the cost of each will certainly do so. As the likely conflict arenas for the coming decade will demand rapid deployment of light forces that cannot avoid low-altitude operation, one must acknowledge that scarce, expensive aircraft will fly in range of a considerable number of lethal anti-aircraft weapons. American aircraft will certainly become more—not less—visible as anti-stealth technologies become more widespread.

Technologies and materials are now available, or are in advanced development, that can substantially reduce the numbers of aircraft and UAVs lost to fires and explosions. These are not statistical loss reductions based upon assumed kill probabilities; a damaged aircraft that survives an otherwise-fatal fire is a real save.

Fire/explosion hardening is a 100 percent payoff option. Unlike defensive measures and countermeasures devised to work against specific threats and sensors, fire/explosion hardening works against anything that can cause a fire or explosion aboard an aircraft. The authors will publish test results from our hardening materials evaluation program in the coming months. ■

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Mr. Kennedy is a munitions designer of worldwide recognition, with more than 50 years experience in the field. Among his many accomplishments include design of anti-aircraft and anti-missile warheads utilizing a wide range of operating principles. Mr. Kennedy is president of D. R. Kennedy & Associates, and has been a member of the Bomb & Warhead section with the NDIA (and its predecessor organizations) for more than 40 years.

Rapid Development of Threat Models

for Countermeasures Development

■ by Mr. David Hardaker, Mr. Mike Durboraw, Mr. Travis Hoener, Mr. Ron Wingenter, and Mr. Jimmy Washington

In recent years, the proliferation of numerous and inexpensive infrared guided, hand-held, anti-aircraft missiles has made the low altitude battlespace an increasingly dangerous place to operate for US and allied forces. These missiles threaten the special operations, transport, and tactical forces that have been so critical to US success in worldwide peacekeeping missions as well as the war on terror. With the widespread proliferation of these threats to forces worldwide, it is critical that information about evolving weapons technology be placed in the hands of countermeasures designers and system developers in a timely manner.

Historically, new threat developments and trends identified by the intelligence community are communicated to countermeasures developers through updated threat documents. Based on this updated threat information, developers either modify existing or develop new threat models for use in the all digital and hardware-in-the-loop simulations that support system development. Countermeasures developers then rely on the intelligence community for validation of the updated threat models. While this methodology has worked reasonably well for many years, keeping up with rapidly improving weapons technology has become increasingly difficult.

Within the intelligence community, a recent initiative called the Threat Modeling and Analysis Program (TMAP) is improving the way new threat information is distributed to countermeasures developers. Under TMAP, the intelligence community will provide not only updated threat documentation but also a functioning digital model of the threat implemented in a commercial off the shelf (COTS) visual programming environment called Simulink[1] developed by The MathWorks. Unlike textual computer languages traditionally used for scientific modeling (e.g. C, C++, FORTRAN), visual languages provide a way for both the model developer and user to view the model in the form of a block diagram or state flow diagram. As depicted in Figure 1, the visual representation of a system model is often very similar to the type of block diagram that a system designer might create in planning for and designing the system itself. Offering the ability to model systems, subsystems, components, and algorithms using easy-to-understand graphical representations, Simulink enables intelligence analysts to capture the entire knowledge base associated with a specific threat system in the form of a working digital model that contains links to basic information as well as validation data.

In addition to enabling new threat information to be disseminated in a form that is easier to understand than with threat reports alone, one of the primary goals of the TMAP initiative is to provide an efficient mechanism by which a Simulink model of a threat system can be exported for use within simulations used by countermeasures developers and system designers. Such a mechanism offers the potential to drastically reduce the time required for new threat information to have an impact on countermeasures development. This article discusses the process of exporting Simulink threat models for use in other simulations and, in particular, describes recent work performed for the Air Force Information Warfare Center (AFIWC) by Dynetics, Inc. to streamline the exporting process.

Exporting Simulink Threat Models

There are several basic approaches to exporting models from Simulink so
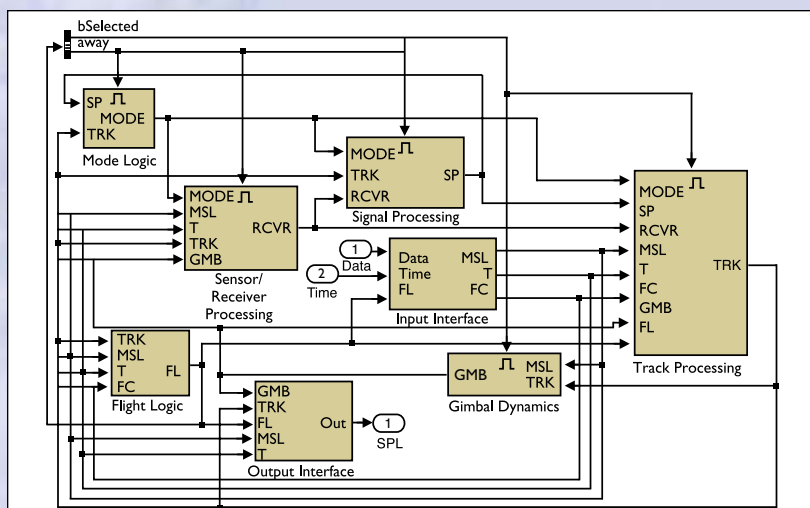

Figure 1. By design, the visual representation of a system model in Simulink very closely resembles the functional block diagram of the system being modeled.

that they can be used within another simulation. First, the Simulink model can be manually converted block-by-block into the programming language of the target simulation. The person doing the code conversion has to be skilled in both Simulink and the target language in order to accurately recreate the Simulink model in the language of the target simulation. The human code converter needs a good understanding of how the Simulink run-time infrastructure works, including how Simulink decides the execution order of blocks within the model and how its differential equation solvers work, in order to faithfully represent the behavior of the model in the target simulation. Based on the skill of the code converter, this approach has the potential to produce code in the target simulation that is optimized (in terms of memory usage, execution speed, or another criterion) because the code converter will be able to take advantage of the best ways to implement the Simulink algorithms in the target language. However, this approach can also be very time consuming and costly if the Simulink model being converted is complex. For example, the Simulink algorithm shown in Figure 2 is simple enough that one can convert it to a C code function quite easily. But a hardware-based model of a threat air-to-air missile seeker may contain thousands of Simulink blocks orga-

nized in many layers of subsystems with many feedback paths and states. In such a situation, converting the Simulink model by hand would be a significant effort.

An alternate approach is to use a process that automatically converts a Simulink model to the language of the target simulation. The MathWorks offers an add-on product to Simulink called Real-Time Workshop (RTW) that converts certain Simulink models to C code. One important consideration in evaluating the cost effectiveness of this kind of automated approach is the extent of model preparations required in order to make the process work. If significant work is required to fashion the threat model so that it is compatible with RTW, then any benefit from having an automated process will clearly be reduced. It is also important to recognize that code generated by such an automated approach may not be sufficiently readable to enable the generated code to be modified and maintained in the target language. In the case of threat models developed by intelligence production centers under the TMAP initiative, this issue should not be a significant driver provided that the threat models are documented well and contain sufficient test points to allow countermeasures and systems designers to adequately examine the

effects of their designs on the modeled threat system.

While automatic conversion will generally not produce code that is as efficient or optimal as the hand-coding approach produces, much less time and effort are typically required in order to perform the conversion. Consequently, for situations where run time and memory requirements are not very stringent and maintenance of the code in the target simulation is not required, automatic conversion offers the potential for a very cost-effective method of exporting Simulink models to other simulations.

Key Considerations

It is important to discuss a few key issues that must be considered regardless of the approach taken in exporting a Simulink model. Perhaps the most important of these issues deals with how the converted code is integrated into a target simulation. First, there will always be the need to manually integrate the converted code by developing an interface layer to provide the connection between the target simulation and the converted code. This interface layer must address how the code is entered functionally as well as how data is transferred into and out of the code. As Figure 3 illustrates, once this interface layer is in place, the Simulink model can be repeatedly updated and converted without having to modify the original interface layer provided that the Simulink model interface does not change. The significance of this statement to the countermeasures developer is that since Simulink threat models will continue to be updated based on new assessments, automated code conversion offers the potential for rapid introduction of the latest threat model into the countermeasures development process.

Secondly, the amount of effort required to develop the interface layer in the first place depends heavily on the degree of similarity between the simulation architecture containing the original Simulink model and the architecture to which the model is being exported. Many large scale simulations written in
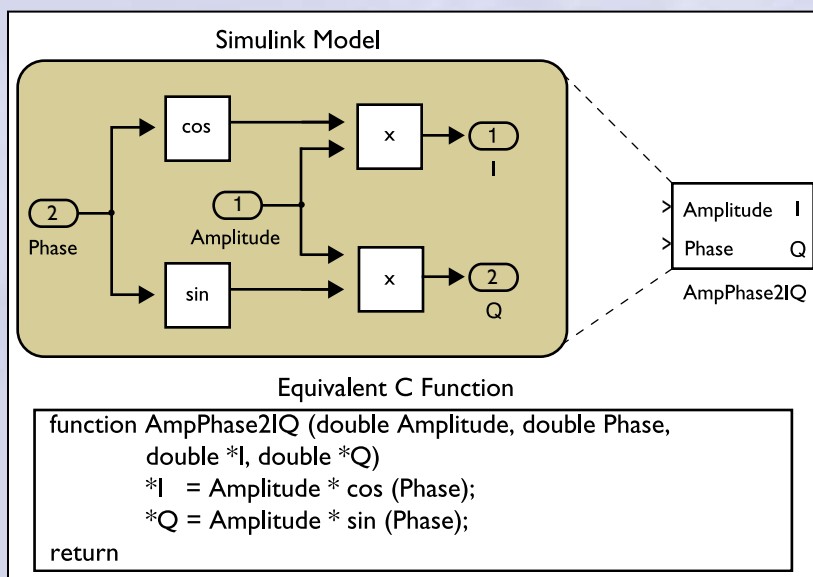
Figure 2. Simple Simulink models can be easily converted to C code.

traditional programming languages have architectures similar to the topology shown in Figure 4, where truth calculations (e.g. relative geometry, signal propagation) are modeled as separate objects or services. If the Simulink host architecture from which the threat model is being exported is similar, then building the interface layer for the threat model will not be difficult. However, if truth calculations are embedded within the ownship and threat models, as in Figure 5, then integrating the exported threat model into the target simulation will be much more involved.

Model fidelity is another key issue that must be considered regardless of the approach taken in exporting a Simulink model. For an exported model to have utility within a simulation supporting countermeasures development, the fidelity of the Simulink model must be sufficient to capture the behavior to be exploited. For example, in order for a threat radar or RF seeker model to adequately support the development and testing of a coordinated range/Doppler deception technique, it must, at a minimum, be able to process a combined signal comprised of the ownship radar return and the transmitted jamming signal. The Simulink environment should not be a limiting factor in this respect – use of Simulink to represent system behavior across the entire spectrum of model fidelity from the simplest effects-level models to the most detailed hardware-based models has been demonstrated over and over again.

Finally, regardless of the approach taken in exporting a Simulink model, the converted code must be verified against the behavior of the original Simulink model. There are several suitable approaches to ensuring that code conversion has not adversely affected a model's behavior. First, if the converted code can be brought back into Simulink and substituted for the original Simulink block, as Figure 6 illustrates, then any test that demonstrated performance of the original Simulink block can also demonstrate performance of the converted code. Simulink provides just
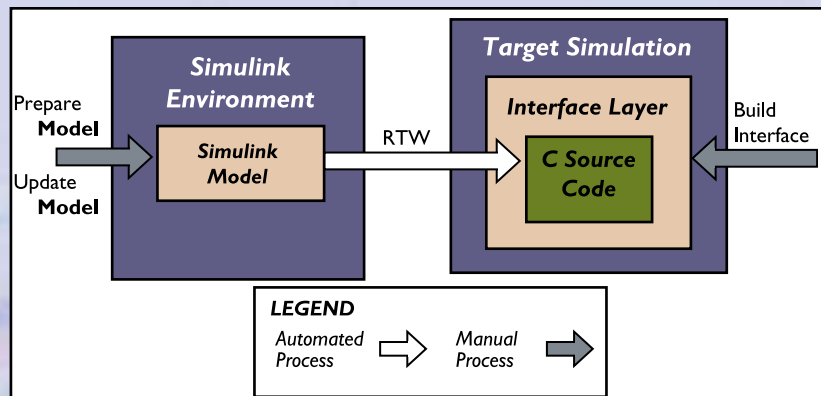

Figure 3. An updated Simulink threat model can be rapidly inserted into the target simulation provided that the interface layer did not change.
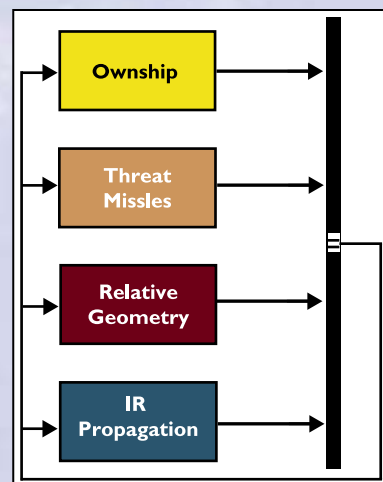

Figure 4. In this topology, the simulation infrastructure (e.g. relative geometry, IR propagation) has been decomposed from other model components.

such a mechanism for integrating legacy code into a Simulink block diagram. Secondly, if Simulink performance tests can be scripted such that model input and output data are saved to disk, then a stand-alone simulation containing the converted code can be constructed fairly easily. As Figure 7 shows, the stand-alone simulation simply pipes the input data into the converted model and saves the output data to disk for comparison with the output of the original model.

Automated Code Conversion

Having discussed many of the issues associated with exporting Simulink threat models in general, there are also some considerations more focused on how well automated code
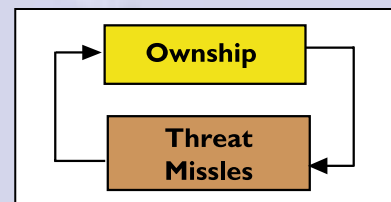

Figure 5. In this topology, the simulation infrastructure is embedded within the model components.

conversion works. As was previously mentioned, RTW provides the basic capability to convert Simulink blocks to C code. However, there are a number of limitations associated with use of RTW. First, a significant amount of effort is required to prepare an arbitrary Simulink model for conversion using RTW. There are certain primitive Simulink blocks that are not compatible with RTW. Block ports and signals must be named in accordance with the requirements for identifiers in C. In addition, all nested input and output data structures (called buses in Simulink) at the outer interface of the block to be converted must be manually broken apart into signal components and routed through individual ports. While not necessarily difficult, these modifications are tedious (especially for complex models) and require some sort of manual updating if any change is made to the underlying signals on the interface. Also, because these changes may not necessarily be desirable as permanent changes to the Simulink model in its native environment, some provision must be made to save and maintain the two different versions of the model.
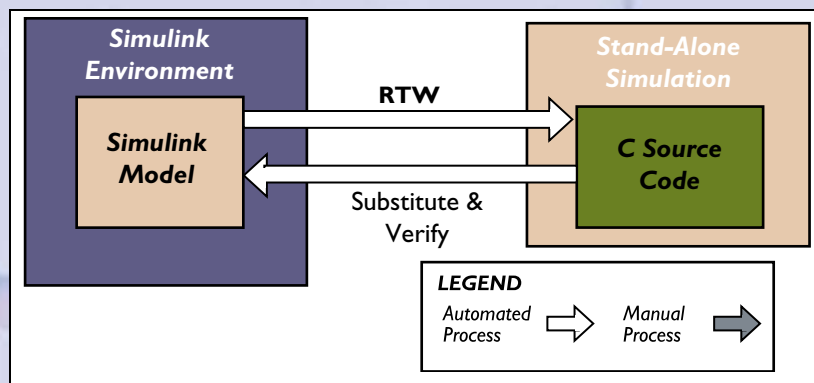
Figure 6. Exported code can be verified in the original Simulink environment..
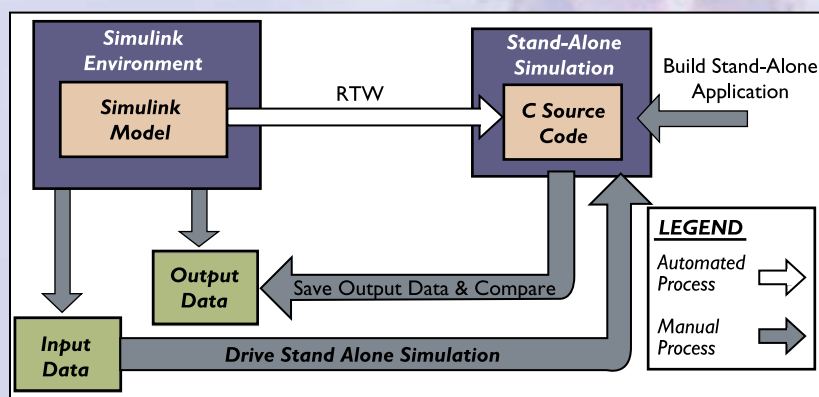

Figure 7. Exported code can be verified in a stand-alone simulation.

Secondly, integration of the RTW-generated C code with another simulation is not straightforward – a significant amount of experience with Simulink and its inner workings is required in order to determine and use entry points into the converted code as well as the input and output data structures that make up the interface.

Although they may seem daunting, the majority of these RTW limitations can be eliminated through customizing the RTW process. As part of our work for AFIWC, Dynetics has recently developed a prototype automated process with the primary goals of minimizing model conversion requirements and maximizing ease of integration of the converted code into other simulations. The automated process 1) conditions an arbitrary Simulink block for use with RTW; 2) converts the Simulink block to C code using RTW; 3) builds a C++ object around the converted C code; 4) constructs a stand-alone C++ project that substantiates and

interacts with the C++ object; and 5) provides the capability to easily switch between native Simulink and compiled code within the Simulink environment for verification purposes. The C++ object has straightforward methods as well as an interface that identically matches the Simulink block interface, including nested data structures. This automated process has been successfully demonstrated on several threat missile seeker models and will continue to be tested and modified to increase its level of robustness.

Final Thoughts

As threat technology continues to become more sophisticated and as threat systems continue to be proliferated, it is essential that countermeasures developers and system designers have access to the most recent threat assessments available. By providing those assessments in the form of threat documents augmented by working digital models and by providing a mechanism by which those digital models can be

easily integrated into other simulations, the TMAP initiative can streamline the process of testing new concepts against an evolving threat. As outlined in this article, there will always be issues related to cost-effectiveness, interfaces, model fidelity, and verification. However, the COTS environment on which TMAP is built offers enormous capability and flexibility in addressing these issues and in making this process more and more efficient.

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1. Simulink and Real-Time Workshop are registered trademarks of The MathWorks.

Addressing Low Altitude Ballistic Penetration & Fire Prediction

in the C–5 Modernization LFT&E Program

■ by Mr. Nathan Cook

This article presents Air Force Live Fire Test and Evaluation (LFT&E) efforts that are establishing the new state of the art for ballistic testing. New technology and testing techniques can provide high fidelity, near real-time data to dry bay fire prediction and vulnerability analysis, bringing ballistic testing into the 21st century.

C–5 LFT&E Team

Under the C–5 Modernization Program, the C–5 Development System Office (ASC/GRA), has teamed with the Operational Analysis Branch of the Aeronautical Systems Center's Engineering Directorate (ASC/ENMM), the 46th Test Wing Aerospace Survivability and Safety Flight (46 OG/OGM/OL–AC), Lockheed Martin Aerospace (LMAero), SURVICE Engineering, and others to accomplish the necessary analyses, tests, and evaluations to fulfill the LFT&E requirements. Ballistic testing of materials, full-scale replica testing with airflow, and other tests are being performed by 46 OG/OGM/OL–AC at Wright-Patterson Air Force Base, OH (WPAFB).

The huge capacity and outsize/oversize capability of the C–5 airlifter are essential to the operating tempo of the current US military mission. The C–5 Modernization Program seeks to extend the useful life and increase the utility of this important platform. C-5 missions include strategic airlift, emergency aeromedical evacuation, and airdrop. Takeoff and approach in potentially hostile environments is a growing reality. Because of the potential threats encountered in the low altitude battlespace during takeoff and landing, the C–5 LFT&E Program includes an assessment of C–5 survivability to low altitude small arms and anti-aircraft artillery (AAA) fire, particularly with respect to low altitude threat induced onboard fire.

The materials ballistic tests were designed to obtain technical data to enhance the understanding of how the C–5 will respond to ballistic impact. Because of the C–5's massive size, the aircraft has unique construction features, such as very thick aluminum structure and thick honeycomb sandwich[1] parts. These unique members affect the functioning[2] of armor-piercing incendiary (API) and high explosive incendiary (HEI) projectiles impacting the aircraft. During the test, representative solid aluminum and honeycomb panels of varying thickness were subjected to API and HEI impacts in Ranges 1 and 2 of the 46 OG/OGM/OL–AC Aerospace Vehicle Survivability Facility (AVSF). This testing was conducted from December 2002 to July 2003.

New Problems, New Solutions

Ballistic panel testing is not new. The basic concept is very simple and the set-up is uncomplicated. A panel of material is shot with a projectile and the effects are measured. Also, there is extensive literature covering API and HEI impact and functioning. Two things set this testing apart from previous work: 1) material thickness and 2) data acquisition technology.

Most previous work involves material thicknesses on the order of 0.01 to 0.25 inch, consistent with most fighters and smaller transports. C–5 material thicknesses are more typically on the order of 0.25 to 4 inches. Armor testing, which involves solid thicknesses of this magnitude, typically uses different material than those used in aerospace vehicle construction. Also, it was unclear how thick honeycomb would affect API and HEI functioning.

Previous data acquisition and visualization technology typically recorded a time history of the incendiary fireball growth and decay, or an idea of the spatial extent of the fireball, but not both. The time history could be measured at a single point or a few points using photodiode flash detectors, but the precise spatial extent was difficult to discern. Open-shutter photography in a darkened range would record the spatial extent of the fireball in two dimensions (2D), but time history information was lost. High-speed film could record
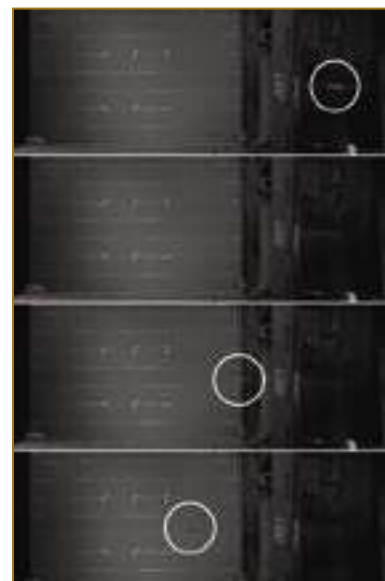

Figure 1. Four frames taken at 4200 pictures per second from an API panel test showing the projectile approaching from right, impacting and exiting the panel.

both 2D spatial extent and time history at rates anywhere from 100 to 1,000,000 pictures per second (pps), but the rolls of film were expensive and cumbersome to view.

Serious Quantitative Results

The development of high speed digital video cameras has progressed to the point where these new cameras now meet or exceed the performance of high speed film cameras. Using Phantom 5 and 7 cameras from Photo-Sonics, Inc., and Vision Research, Inc., the 46 OG/OGM/OL–AC can record ballistic test events with sufficient speed and resolution to provide excellent qualitative and quantitative results, as shown in Figure 1 (see page 45).

The digital video is downloaded from the camera directly into a laptop computer immediately upon test completion, ready for viewing, and the test engineer can evaluate the test conduct and setup. This allows for real time test setup optimization. Shots can be repeated, if necessary, without delay. This saves time and money involved with breaking down and setting up test equipment. Keeping the customer apprised of test conduct is made easy by converting the video to AVI format, which is easily incorporated into papers and presentations.

An extensive, detailed amount of quantitative data can be extracted from feeding these images into TrackEye Motion Analysis (TEMA) software from Photo-Sonics, Inc., and Image Systems AB. Three dimensional (3D) positions and velocities at each time step for projectiles and spall can be generated, as shown in Figure 2. Using a technology originally applied to airbag tracking in the automotive crash test community, 2D cross-sectional positions and areas at each time step of incendiary and high explosive fireball can also be generated, as shown in Figure 3. Volume estimation using the area measurements is a capability being developed by Image Systems and test engineers at 46 OG/OGM/OL–AC.

In other words, with the set-up described above, the complete time history and spatial extent of the incendiary fireball can be measured from initiation through maximum volume to decay. In addition, 3D impact and residual velocities can be recorded, allowing for high fidelity validation of vulnerability models. This capability, made possible by developments in complementary metal-oxide semiconductor (CMOS) sensors and the high-performance of today's personal computers, truly brings ballistic testing into the 21st century.

Unexpected Effects

One other aspect of previous work that sets this testing apart was the typical focus in the past on the exit face incendiary effects. That is, the projectile would impact the panel on the entrance face, penetrate, and move through to the opposite side, carrying incendiary and/or high explosive material with it. Often the determination of "function type" (the extent to which the incendiary or explosive is consumed in the fireball) relied exclusively upon the exit face effects. Entrance face incendiary effects were not typically measured.

As can be seen in Figure 4, the entrance face incendiary effects can be much greater in magnitude than the exit face incendiary effects, especially for certain combinations of material thickness, panel obliquity, projectile yaw, and impact velocity.

Figure 2. TEMA window showing projectile tracking and measurement
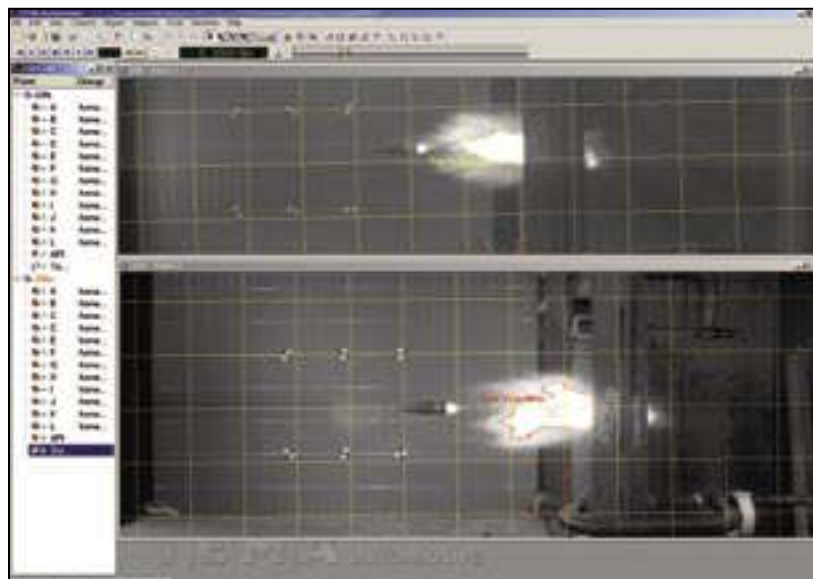

Figure 3. TEMA window showing fireball cross-section measurement

This has important implications for fire prediction, depending on impact location on the airframe. This surprising development led to a change in the position of the cameras, the categorization of function type, and the planned shot matrix.

Test–Model–Test

The quantitative information gleaned from these tests will be fed into the Fire Prediction Model to help estimate the vulnerability of the C–5 and provide pre-test predictions for later C–5 LFT&E shots, such as the full-scale replica known as the "Iron Bird." "Iron Birds" are built from steel instead of aluminum to withstand multiple tests. Ultimately, a much better understanding of the C–5's survivability will result because of the application of these technological advances. ∎

Mr. Nathan Cook is an Aerospace Engineer in the 46th Test Wing Aerospace Survivability and Safety Flight, Wright-Patterson AFB OH. He has worked with JSF, C–5, and C–130J tests, and with development of new techniques using the latest digital imaging and analysis technology. He holds a BS in Physics from Harvey Mudd College, an MEd from Converse College, and an MSME from the Georgia Institute of Technology. He can be reached at nathan.cook@wpafb.af.mil.

Endnotes
1. Honeycomb sandwich construction is a standard technique, whereby a core of honeycomb is set between two thin sheets. The sheets are attached to the core with adhesive. The sandwich is mostly void space, but very rigid, offering a great strength to weight ratio.
2. "Functioning" refers here to the ignition and burning of the incendiary material of an API round or to the fuze of an HEI working correctly and leading to a detonation of the high-explosive material.
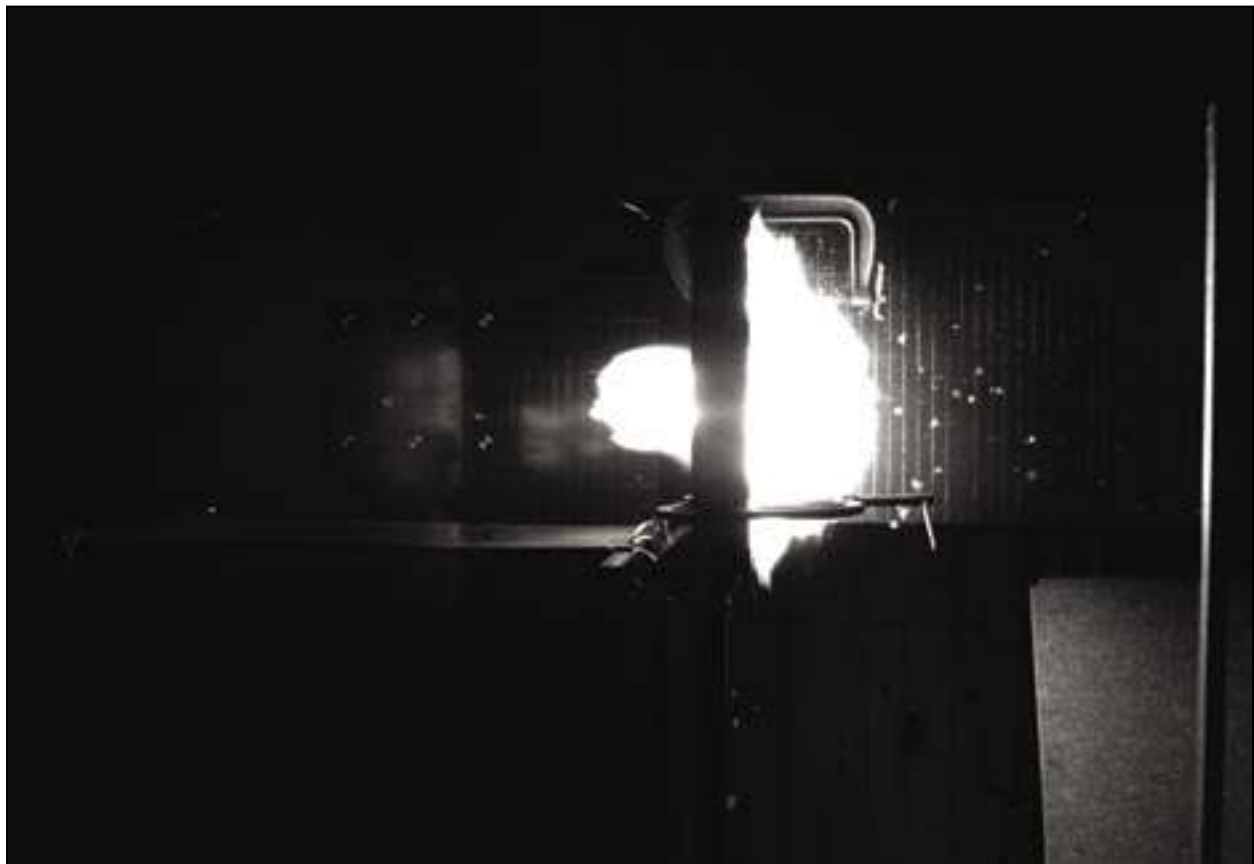

Figure 4. Entrance face effects (fireball to right of panel) were much greater than expected

Calendar of Events

NOV

17–20, Palm Springs, CA
41st Annual Air Targets, UAVs,
and Range Operations
asaliski@ndia.org

18–20, Nellis AFB, NV
Brawler and ESAMS Users
Group Meeting
jeng_paul@bah.comm

DEC

8–11, Las Cruces, NM
International Test and Evaluation
Association Modeling and
Simulation Workshop
www.itea.org

JAN

5–8, Reno, NV
42nd AIAA Aerospace Sciences
Conference and Expo
www.aiaa.org

26–29, Los Angeles, CA
Annual Reliability and
Maintainability Symposium (RAMS)
Dr. William Robertson, 703.550.9436

FEB

3–5, Monterey, CA
Strategic and Tactical Missile
Systems Conference
www.aiaa.org

4–6, Washington, DC
15th Annual NDIA SO/LIC
Symposium/Exposition
www.ndia.org

MAR

9–11, San Diego, CA
Advanced Technology Electronic
Defense Systems (ATEDS) Review
Jack Kress, 812.279.9195
www.ateds.com

Information for inclusion in the
Calendar of Events may be sent to:

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